

University of Southern Queensland
Faculty of Engineering and Surveying

**Analysis and Modeling of Grouting
and its Application
In
Civil Engineering**

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ABSTRACT

Grouting is a popular ground treatment technique, but not so many engineers are familiar with it. And they often have misconception about grouting. The project is to clarify on one hand the basics of grouting, and then on the other hand try to provide a full coverage of all types of grouting mechanisms in practice. For each grouting mechanism, a brief discussion is given to its design considerations, construction and application. Finally, finite element method is used to analyze and model grouting to confirm the extent of grouting in terms of treatment zone and degree of improvement of ground properties required.

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A. Different Types of Grouting

Chapter 1. Introduction

Grouting is a kind of ground treatment techniques used quite often in underground civil engineering works. Yet it is seldom touched in the course works. To many engineers, grouting is something mysterious and always confused by the many different terms used.

Therefore, the project will first clarify the basics of grouting so as to eliminate all the illusions and misunderstandings about grouting.

Then the project will review five types of grouting techniques and their working mechanisms. The five grouting techniques selected are the Rock Fissure grouting, the TAM grouting, the Compaction grouting, the Compensation grouting and the Jetting grouting. They should be representative and should have embraced all grouting mechanisms currently in practice.

There may be variances for each grouting technique, but it is not the intention of this project to look into such details.

For each selected grouting technique, particulars of the technique will be given, including its injection mechanism, improvement of ground properties, general grouting scheme design considerations, construction and application.

Finally, finite element method is used to analyze and model grouting to confirm the extent of grouting in terms of treatment zone and degree of improvement of ground properties required.

Chapter 2. Background information

Grouting has been using in civil engineering for quite a long time. Its traceable record can be as early as in the beginning of 1800s.

- In 1802, the idea of improving the bearing capacity under a sluice by the injection of self-hardening cementitious slurry was first introduced (Henn 1996).
- In 1864, Peter Barlow patented a cylindrical one-piece tunnel shield which could fill the annular void left by the tail of the shield with grout. And it is the first recorded use cementitious grout in underground construction (Henn 1996).
- In 1893, the first systematic grouting of rock in the USA as performed at the New Croton Dam, in New York (Henn 1996).
- In 1960s, jet grouting technique was developed (Henn 1996).
- In 1977, first application of compaction grouting for controlling ground movement during construction of the Bolton Hill Tunnel (Henn 1996).
- In 1995, the first industrial application of the compensation grouting concept was conducted at the construction site of the Jubilee Line Extension Project in London (Gilles Buchet et al 1999).

Initially, its application confines mainly in void filling, water stopping and consolidation. Nowadays, it extends to alleviate settlement of ground caused by basement and tunnel excavation works, to strengthen ground so that it can be used as a structural member or retaining structure in solving geotechnical problems.

Grouting, instead of an old and obsolete ground treatment technique, it is still developing in both methodology as well as hardware engineering. And its application is extending in the civil engineering field, from small-scale remedial work site to very large-scale project site. It is still the most popular ground treatment method used today.

Chapter 3. Methodology

The methodology adopted is to review the fundamental concept of grouting in the beginning. Discussion will be brief but aim at giving the correct concept as far as possible for the grouting technique. Then identify the working mechanisms of the five selected grouting techniques to find out how it work to achieve the grouting purpose. The selected grouting techniques are the Rock Fissure grouting, TAM grouting, Compaction grouting, Compensation grouting and the Jet grouting.

Based on the findings, review the relevant grouting parameters for designing a grouting scheme for each selected grouting technique, construction particulars and in which aspect it performs best.

Finally, define the extent of grouting in terms of treatment dimensions and degree of ground property improvement by means of geotechnical modeling and analysis with 2D finite element software. In this project, the PLAXIS version 7.2 will be used mainly. And version 8 will be used for analysis that requires the function of applying a volumetric strain in volume clusters.

Details of the finite element analysis will not be given other than the important procedures e.g. the geometry model, the initial conditions (both the pore water pressure and the stress), the material properties and the calculation phases.

Examples are made up projects, not real cases as the aim of the analysis and modeling is to illustrate the grouting application only.

Eventually, conclusions are drawn regarding application of grouting technique in water stopping, ground strengthening and control of ground settlement.

Chapter 4. Basics of Grouting

4.1 The Ground

Grouting is the process to inject grout into the ground. Hence, the volume of the ground ready to accept grout is the primary consideration before any other considerations.

In rock, the groutable volume exists in the form of fissures and joints. And in soil it is in the form of pores or voids in between the soil particles. Some literatures refer such fissures, pore and voids as the POROSITY of rock/soil. In this project, porosity will be used exclusively for soils.

Volume is just one factor to consider but not the only one. The other factors that need to be considered are the size or aperture of the volume and the resistance of the ground material.

If the size of the voids or the aperture of the fissures is too small for the grout to go in, it is still not groutable. On the other hand, if the soil is too hard to break, some grouting techniques cannot be applied then.

Therefore, the most important aim of the ground investigation for grouting is to identify if or not the ground is suitable for the intended grouting technique i.e. groutability of the ground. Generally, field-testing is required to find it out. For certain grouting techniques, high quality sampling is also required. Details shall be discussed in more detail in the following chapters.

Once the groutability of the ground is confirmed, it is required to find the rock or soil data that is required for the determination of the various grouting parameters to achieve the intended grouting result. This topic will be discussed in more detail for the selected grouting technique.

4.2 The Grout

GROUT can be defined as a solution, an emulsion or suspension in water, which will harden after a certain time interval. It can be divided into two main groups:

- a. Suspension Grout
- b. Liquid Grout or Solution Grout.

Suspension grout is a mixture of one or several inert materials like cement, clays etc. suspended in a fluid -- water.

According to its dry matter content it is either of the stable or unstable type. Unstable suspension grout is a mixture of pure cement with water. An agitation process is

required to form the mixture. Sedimentation of the suspended particles rapidly occurs when the agitation stops.

Stable suspension grouts are generally obtained by using the following methods:

- a. An increase of the total dry matter content
- b. The inclusion of a mineral or colloidal component, often from the bentonite family
- c. The inclusion of sodium silicate in cement and clay/cement suspensions.

The apparent stability obtained depends on the dosage of the various components and on the agitation process. It is relative since sedimentation occurs more or less as soon as agitation stops.

Liquid grout or solution grout consists of chemical products in a solution or an emulsion form and their reagents. The most frequently used products are sodium silicate and certain resins.

The project does not aim at a very detailed study on this topic, so only the cement-based grout and the sodium silicate-based grout will be discussed in brief.

4.2.1 Cement-based Grouts

Cement-based grouts are the most frequently used in both water stopping and strengthening treatment. They are characterized by their water cement ratio and their Total Dry Matter / Water weight ratio. The properties and characteristics of these grouts vary according to the mix proportions used. However, they have the following properties and characteristics in common.

- a. Stability and fluidity according to the dosage of the various components and their quality
- b. Unconfined compressive strength linked to water cement ratio
- c. Durability depending on the quantity and quality of the components
- d. Easy preparation and availability
- e. Ease of use
- f. Relatively low cost mixes

The cement-base grouts can be divided into three main groups, namely the pure cement grout, the bentonite cement mixes and the grouts with fillers.

4.2.1.1 Pure cement grout

It is an unstable grout. However, bleeding can be avoided with water cement ratio less than 0.67. Usual mix proportions are from water cement ratio 0.4 to 1 for grouting. Very high mechanical strength can be attained with this type of grout. During grouting, cement grains deposit in inter-granular voids or fissures is analogous to a kind of hydraulic filling. The grout usually undergoes a significant filtration effect. The grain fineness is an important factor for fine fissures.

4.2.1.2 Bentonite cement grout

It is a stable grout. When bentonite is added to a cement suspension, the effects are: -

- a. Obtain a homogeneous colloidal mix with a wide range of viscosity.
- b. Avoid cement sedimentation during grouting.
- c. Decrease the setting time index and separation filtering processes.
- d. Increase the cement binding time.
- e. Improve the penetration in compact type soils
- f. Obtain a wide range of mechanical strength values.

In water stopping, grout will include a lot of bentonite and little cement. In consolidation works, grout will contain a lot of cement and little bentonite. Ideal mixes should be both stable and easy to pump. Viscosity measured by means of a “Marsh” cone may vary from 35s to 60s. Bleeding rate usually stays under 5% in 2 hours.

4.2.1.3 Grouts with fillers

Fillers are added in order to modify the viscosity of a given grout so as to obtain a low cost product to substitute the cement. The most commonly used fillers are the natural sands and fly ash from thermal power stations. The term “mortar” is commonly used to specify grouts with fillers that have a high sand content. Adding fillers reduces the grout penetrability, as the fillers are of larger grain sizes.

Grouts with fillers are used when water absorption and/or the size of voids are such that filling becomes essential and when the leaking of grout into adjoining areas should be limited. In addition, fillers in grout will produce low slump grout with high viscosity for certain grouting purposes.

4.2.2 Silicate Based Grouts

Silicate based grouts are sodium silicate in liquid form diluted and containing a reagent. Their viscosity changes with time to reach a solid state that is called the “gel”. They are used in soils with low permeability values such that all suspension grouts cannot penetrate. According to the type of grout used, the gel obtained will be water-tightness and/or with strength that are temporary or permanent.

When the temperature of a silicate decreases, its viscosity increases very rapidly. This temperature should not fall below 0 degree C in order to eliminate any risks of modification of its properties.

The reagent can be of mineral type or the organic type depending on the treatment purposes. Examples of the mineral type reagents are the sodium aluminate and the sodium bicarbonate. The formed gel is usually termed “soft gel” as they are mainly for water stopping purpose with very little strength improvement of the soil.

Examples of the organic reagents are the monoester, diester, triester, and aldehyde. With a high content of silicate and pure organic reagent, high strength improvement of the soil can be attained. The gel is usually called “hard gel”.

The range of the mix proportions per meter cube of grout used is as follows: -

Reagents	40 to 150 litres
Sodium silicate, 35 – 37 Baume degrees	180 to 800 litres
Water	(added to make up 1000 litres)

The main characteristics of silicate-based grouts in liquid form are: -

- a. The density is linked to its silicate ratio.
- b. The initial viscosity depends on the silicate content and concentration.
- c. The evolutive viscosity is apt to change until setting time.
- d. The setting time is defined as the time from the freshly mixed stage until the moment the grout becomes hard and no longer flows. It can be adjusted from few minutes to two hours by means of the variation in the quality and quantity of reagents added.

4.2.2.1 Soft gels

It is mainly for water stopping purpose. They are gels with a very low dosage in silicate in which the gelling process is most generally obtained by adding a mineral reagent. Their very low degree of viscosity (close to water) ensures the injection of very fine sand to achieve the water stopping purpose.

Reduction in permeability can be up to 1×10^{-6} m/s and, in some case even up to 1×10^{-7} m/s when more lines of grout holes are added. There is also a slight improvement in strength, about 0.2 MPa.

4.2.2.2 Hard gels

They are obtained with high content of sodium silicate in grout and an extra purified organic reagent. The amount of hardening agents is selected in view of attaining the best possible neutralization rate. The most commonly used reagents are esters and aldehydes.

Their initial degree of viscosity is high. The strength improvement e.g. in sand can be from 0.3 MPa to 6 MPa. They are used in the consolidation of granular soil and finely fissured rock. High grouting pressure is required to achieve the intended grouting purpose because of the high viscosity of the grout.

Tri-axial tests on the recovered grout samples show that the increased breaking strength of a granular soil treated with hard gel is mostly due to the increased cohesion.

4.3 Injection Method

GROUTING is the process in which grout in liquid form is pumped or jetted into the ground and then hardens. Grouting is also known as INJECTION in some literatures.

Up through the history there has not been much development on the basic injection method. The process of pumping grout under pressure into the ground is still the same until the invention of the jet grouting technique.

Different grout injection methods have been developed for different grouting techniques. In conclusion, there are four main injection methods to inject grout into the ground.

4.3.1 Drill Hole Method

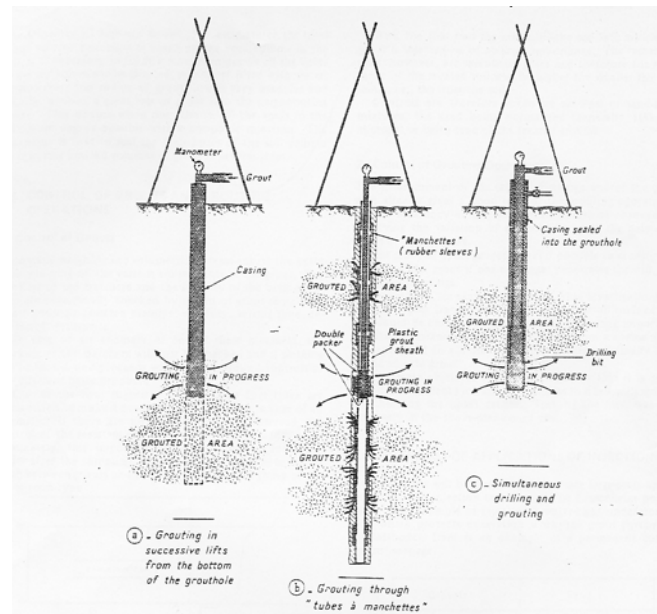
A hole is drilled through the pores/voids of the ground. Then grout is pumped via the grouting line into the surrounding ground of a section with the use of single or double packers.

4.3.2 Drill Tool Method

It is a one-stage grouting method by means of the drill casings or rods. There are two injection methods.

A very permeable soil may be injected during rotary drilling. During the drilling of the grout hole, each time a predetermined distance has been reached the drill rod is withdrawn a certain length and the grout is injected through the drill rod into the section of soil drilled. During each injection the top of the grout hole, a collar is used to seal the gap between the hole and the drill rod.

A variance to this method is to use the grout for flushing during drilling so that some pre-treatment of the ground is achieved.



Injection Methods

The other method, more frequently employed for one-stage grouting is to drive a casing to full depth, withdraw the casing at a predetermined length, and inject through it. This method is effective only if the grout does not emerge outside the casing and the hole wall to the ground surface. Hence, higher grouting pressure is not possible unless the grout is of low slump like the one used for compaction grouting. Refer the above figure (a) and (c) diagrams for details.

4.3.3 Grout Pipe Method

Grout pipes are installed in drilled hole for later on grout injection operation. The gaps between the grout pipe and the drilled hole are normally sealed. When compared with above Drill Tool Method, it is more flexible as the drilling plant is not engaged in the grouting operation.

For multiple-stage grouting, the sealed-in sleeve pipe injection method (the tube-à-manchettes method) is used. It allows several successive injections in the same zone. The method is to place a grout pipe with rubber sleeves into a grout hole, which is

kept open by casing or by mud. This pipe is then permanently sealed in with a sleeve grout composed of a bentonite-cement grout.

The sleeve grout seals the grout holes between the pipe and the soil to prevent the injection grout from emerging along the grout pipe and the hole to the ground surface. This means that, under pressure, the injection grout will break through in radial directions and penetrate into the soil. It may take from 2 MPa to 7 MPa to break the sleeve grout surrounding a rubber sleeve, depending on the resistance of the surrounding soil. If the soil is like the highly decomposed rock, the rubber sleeves will not be opened and thus subsequent grouting is prohibited.

The sleeve pipe consists of a steel or PVC tube with a diameter of 25mm to 50mm. PVC tubes are used to facilitate excavation work afterwards.

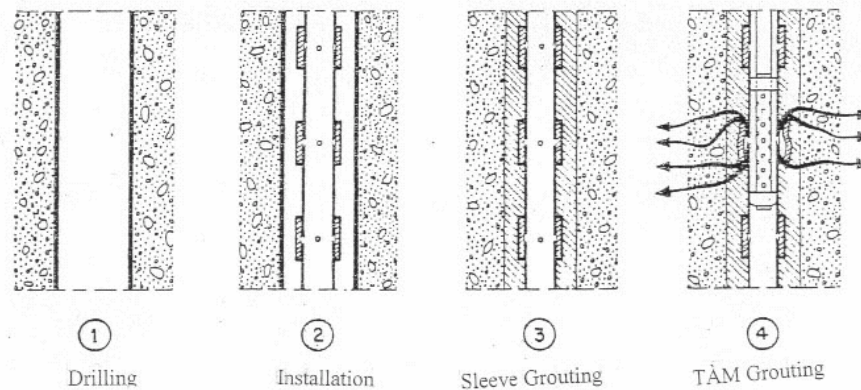
At 33cm intervals or 1m for some cases, small holes are drilled in the pipe to serve as outlets for the grout. The holes are tightly covered by rubber sleeves (manchettes), which will open only under pressure. The holes and sleeves work as one-way valves.

The sleeve pipes are used only in the grouting zone, whereas plain pipes are used for the rest of the grout hole.

In order to inject through a sleeve, a double packer fixed at the end of a smaller-diameter injection pipe is inserted into the sleeve pipe and centered around the sleeve to form a closed chamber with one-way valve outlets. TÀM grouting is the most commonly used grouting technique for grouting in soil. Refer Figure: Injection Methods (b) and the following diagram for details of TÀM grouting.

Advantages of the TÀM grouting technique: -

- a. It is possible to inject grout precisely at locations required.
- b. The manchettes, which act as one-way valves, prevent the injected grout from flowing back into the grout pipe under high grouting pressure. Thus good grouting effect is attained.
- c. It enables re-grouting, which permits the use of grouts with decreasing viscosities. This permits better penetration of the fine voids after the big ones have been closed. More permeable soil layers can be sealed first regardless of the order of injection level, which prevents loss of high-cost, low-viscosity grouts.
- d. The grouting operations are carried out completely independent of drilling and it is very convenient for job organization and the use of grouting and drilling plant.



Details of Tube-à-Manchettes Grouting Technique

4.3.4 Jetting Method

Finally, a different type of injection method, the jet grouting method, is introduced in the 60s, which has a revolutionary change to the grouting concept so far. The grout, with the aid of high pressure cutting jets of water or cement grout having a nozzle exit velocity $\geq 100\text{m/sec}$ and with air-shrouded cut the soil around the predrilled hole.

The cut soil is rearranged and mixed with the cement grout. The soil cement mix is partly flushed out to the top of the predrilled hole through the annular space between the jet grouting rods and the hole wall. Different shape of such soil cement mix can be produced to suit the geotechnical solution. The cutting distance of the jet varies according to the soil type to be treated, the configuration of the nozzle system, the combination of water, cement and shrouded-air, and can reach as far as 2.5m.

Since this grouting technique runs on a totally different concept, the following discussion will not apply to this technique. Instead, the grouting basics of this technique will be touched in details in the respective chapter.

4.4 Injection Pressure

Discussion of injection pressure usually leads to divide opinion because theoretical considerations do not always agree with practical experience.

The pressure, which is measured at the entry of a grout hole, is always higher than the overburden pressure at the level of injection; otherwise, it would not be possible to inject a soil, say, 5m underneath ground surface with 500kPa pressure without encountering considerable uplifts.

For solution grout, it may be possible to use the Darcy Law to explain the relationship between various factors. The reason to use this Law is that solution grout is more or

less similar to ground water before it starts to set. Both of them flow through the pores/voids of the soil. If the Darcy Law is able to describe the ground water flow, why not to explain the penetration of solution grout in soil.

Darcy Law: $Q = K (H_2 - H_1)/B$, where

Q = Discharge of ground water (solution grout)

K = Permeability of the surrounding soil

H_2 = High pressure head (injection pressure)

H_1 = Low pressure head (ground water pressure)

B = Distance between the two pressure head points (the grout spread radius).

Rearranging, the equation becomes $H_2 = H_1 + Q B / K$

Hence, from the equation, it can be seen that the injection pressure is directly proportional to the injection rate (pumping rate); the grout spread radius (hole spacing) and the ground water head. And it is inversely proportional to the soil permeability i.e. the finer the soil, the higher the injection pressure required.

In addition, it also depends on the viscosity of the grout that may change with time, and on the obstacles through which the grout passes to reach the soil e.g. the rubber sleeves, the cracked sleeve grout sheath etc. The latter factors are related to fluid mechanics.

When the grout is flowing, there is a high hydraulic loss during grouting and thus will induce a very high grouting pressure. Therefore, one should distinct the grouting pressure (the dynamic pressure) and the grouting lock off pressure (the static pressure).

For economic reasons and larger spread radius of the grout, a high rate of discharge is desired. However, this rate is limited by the pressure, which the soil can support in order to avoid ground fracturing, surface leaks and heaving.

For suspension grouts, more or less the same rules apply. High grouting pressure is required for small fissures and joints, for grout with high viscosity; for large grouting spread radius and high backwater pressure.

However, some grouting techniques may require high grouting pressure to displace or fracture the ground in order to achieve the desired grouting purposes e.g. Compaction Grouting technique.

4.5 Injection Volume

The estimate of the total grout volume necessary is based on the pore or void volume of the soil. The indicator is the porosity of the soil. Porosity is defined as: total void space / total volume of soil. Some pores are dead-ended or not interconnected. Hence,

Total porosity = Effective porosity + Ineffective porosity

However, the radius of grout flow is very irregular and usually involves a great loss of grout into the neighboring zones. This occurs when one tries to fill the voids to the maximum degree possible with a one-stage injection. One should try first to seal the boundaries of the soil mass to be treated by injecting limited volumes of grout in several stages.

For rock, it is the joints and fissures that take the grout. The grout volume depends on the grading and joint spacing of the rock mass.

Sometimes, the grout volume depends on the grouting result required like in Compensation Grouting. The injection grout volume is related to the settlement improvement attained.

4.6 Grout Hole Pattern

The fissures and joints of a rock mass is always much larger than the pores/voids between the soil particles. Hydraulic loss during grouting is much less accordingly. Therefore, the hole spacing for rock grouting is always wider than that for soil grouting.

Recall the above Darcy Law for the solution grout for grouting in soil. After rearranging, it becomes

$$B = K (H_2 - H_1) / Q$$

The hole spacing relates to grouting rate to be used, the permeability of ground to be treated, and the allowable grouting pressure. Again the fluid mechanic factors also contribute to the hole spacing determination.

With too closely spaced hole pattern, even though more cost for the drilling work at least grout is sent to where it needs. But, if the holes are too widely spaced, the soil or rock mass to be treated will not have grout cover for the whole mass. Although some drilling cost maybe saved, the adverse consequence is great. Hence, it would be rather to drill more grout holes than not doing so. The only thing to observe is that the injection grout volume is based on the total volume of soil or rock mass to be treated and is evenly distributed among the grout holes and grout sections.

There are mainly three different types of grout hole patterns used for grouting works, namely the random spacing, the fixed spacing and split spacing.

4.6.1 Random spacing

It has no fixed pattern of grout hole and the holes are located at where the problems are. It usually applies for small remedial grouting works or for openings of cofferdam because of the underground utilities or other reasons.

4.6.2 Fixed spacing

As it is called, it has a fixed pattern of grout holes. The hole pattern and hole depth should follow the geometric shape of the soil or rock mass to be treated. The spacing should cope with the type of grouting technique used. For grouting in rock, the spacing is normally from 1m to 5m. And for grouting in soil, it is from 1m to 2.8m.

It would be safer to try different spacing and use the one with the best result. However, if there is a lot of job reference, it can be adopted as it is. This type of spacing is used for grouting treatment with regular shape like the grout curtain underneath a dam, grout plug and curtain surrounding a cofferdam.

4.6.3 Split spacing

It is the procedure of locating the primary holes first, and then locating the secondary and tertiary holes between the primary and subsequent series or so to progressively decrease the inter-hole spacing.

Primary holes are the first series of holes drilled at the maximum spacing along a given axis of hole pattern. Secondary holes are the second series of holes drilled midway between the primary holes, and tertiary holes are the third series of holes drilled midway between the primary and the secondary holes both along the same axis.

This type of hole spacing is used for permanent grouting work of important feature like the dam. With this type of hole spacing plus frequent field testing to check the grouting result, the grouting quality is guaranteed at a reasonable cost.

Chapter 5. Different Types of Grouting Mechanisms

There are lots of names as far as grouting techniques are concerned. They can be categorized according to their functions, their grout materials used etc. Please refer Appendix A for details of the different grouting techniques available.

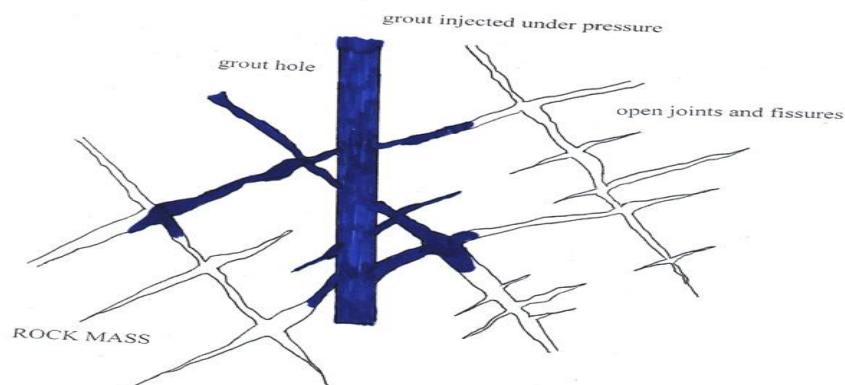
In this project, only five types of grouting techniques will be discussed in depth, namely the Rock Fissure Grouting, the TAM Grouting, the Compaction Grouting, the Compensation Grouting and the Jet Grouting. The five selected grouting techniques should have covered the basic mechanisms of all existing grouting techniques.

5.1 Rock Fissure Grouting

Rock fissure grouting is the use of a hole drilled through the fissures and joints of a rock mass to allow grout to be injected at close centers vertically and re-injecting, if necessary.

5.1.1 Grouting Mechanism

There is only one grouting mechanism for rock grouting. The following schematic diagrams show how is the mechanism for grouting in rock. The grout is injected under pressure through the grout hole drilled into the rock mass to be treated.



Grouting in Progress



Grouting Completed

Schematic Diagram of the Void Filling Mechanism for Rock Fissure Grouting

The voids in the forms of rock fissures and open joints are filled with the grout injected under pressure with partial or complete displacement of infilling ground water. When the grout has set, the open joints or fissures are sealed. In the case of fractured rock zones, the rock fragments or larger blocks are cemented together as an entity rock mass.

After grouting, the permeability of the rock mass will be improved significantly. For fractured rocks, the strength of the rock mass will be increased as well.

5.1.2 Grouting Scheme Design Considerations

Ground investigation work should be carried out to recover rock cores to get the information like rock type, degree of weathering, joint spacing, strength and density. The rock core samples should be recovered at several locations of the grouting site concerned. The main requirement is that the samples are representative of the site so that the dominant property of the rock mass is identified.

The recovered rock cores provide information of the rock joint spacing, which gives an estimate of the approximate rock mass permeability value. This is a field judgment of the likely magnitude of the permeability value k expressed in m/s units for a rock mass.

However, it should take into account both the intergranular and the discontinuity components of flow. Ranges of k values are more realistic than single values. The following descriptive scheme in Table 1 provides generalized values for jointed rock.

However, in order to know if or not the rock mass is suitable for rock fissure grouting, it is required to have some idea about the actual size of the joints and fissures. There is no direct method for such measurement. Only indirect methods are used. The most commonly used method is the Lugeon Test.

Rock Mass Description	Permeability Value	
	Term	k(m/s)
Very closely to extremely closely spaced joints	Highly permeable	$10^{-2} - 1$
Closely to moderately widely spaced joints	Moderately permeable	$10^{-5} - 10^{-2}$
Widely to very widely spaced joints	Slightly permeable	$10^{-9} - 10^{-5}$
Unjointed, solid	Effectively impermeable	$< 10^{-9}$

Table 1: Generalized Values of Permeability for Jointed Rock

It is a test to measure the likely water absorption of the rock mass. Refer the Appendix C for details of the testing procedures. The more joints and fissures of the rock mass are, the higher the Lugeon unit i.e. higher water absorption of the rock mass.

The result of the Lugeon tests will determine the groutability of the rock mass and the type of grout to be used. Refer the following table for details.

Lugeon Units	Grout Usage
1 – 3	No grouting
3 – 10	Microfine cement or chemical grout
> 10	Ordinary Portland cement grout

Table 2: Grout Usage for Different Lugeon Units

Another approach to predict if grouting is required or not is to use information on rock type and rock quality. Different types and quality of rock would statistically yield different inflows. Such an approach has been introduced and used with some success in Hong Kong (McFeat-Smith et al,1998). High, average and low inflows can be calculated for different rock classes using factors for size of water source, head factor and horizontal separation from the water source. And thus the necessity and suitability of grouting technique can be determined.

Grout property consideration relates mainly to the grout particle size, strength and setting time. Normally, choice is based on the void openings of the rock mass i.e. the aperture of the fissures and joints, and the purpose of the grouting scheme.

The ideal grout is a grout that has excellent flow properties and penetration into fine fissures initially, but that, as the traveling speed slows down a distance from the hole, starts to thicken and resist further displacement.

In the old days, pure cement grout is used for grouting. As thick cement grout has high viscosity and will limit the grout penetration in rock, grouting normally starts with dilute cement grout and ended with thick cement grout (Orjan 2004). The dilute cement grout has adverse effects and many grouting done in the 60s for dams are having problems now.

The other disadvantage of pure cement grout is that the grout is not stable. Under high grouting pressure, the cement particles will segregate, causing blocking of the grout path and prevent proper treatment of the rock mass.

Nowadays, bentonite is added into the cement grout as plasticizer and the mixture is a stable suspension. The cement bentonite grout or bentonite cement grout as other literatures may call it is the most commonly used grout for rock fissure grouting. The typical mix proportions per meter cube of grout is as follows:-

Water	870 litre
Cement	350 kg
Bentonite	35 kg

Grouting pressure relates to the in-situ overburden pressure at the grouting depth. In theory, the maximum grouting pressure should be less than the overburden pressure. Above that pressure, joint / fissure will be opened and hydraulic fracture of rock may occur if the rock is poor and shattered.

For good penetration into fissures, it is beneficial to use a high pressure. For pre-grouting in hard rocks pressures applied usually vary from 1 MPa to 6 MPa, depending on thickness of overlaying rock and the strength of the rock, whilst the pressure for post-grouting from within the opened tunnel has normally to be limited to 0.5 MPa to 1 MPa.

However, when it concerns the improvement of rock quality by grouting, Barton and Quadros(2003) have in their paper “while grout is still flowing, there is such a steep gradient away from the injection holes that ‘damage’ to the rock mass is limited to local, near borehole, joint aperture increase,”. For hydraulic fracturing to take place, usually pressures well in excess of 15 MPa is required in competent rock.

The grouting pressure shall only exceed slightly the overburden pressure if the rock is poor and shattered. In good rock, it maybe increased up to five times the overburden pressure (Henn 1996).

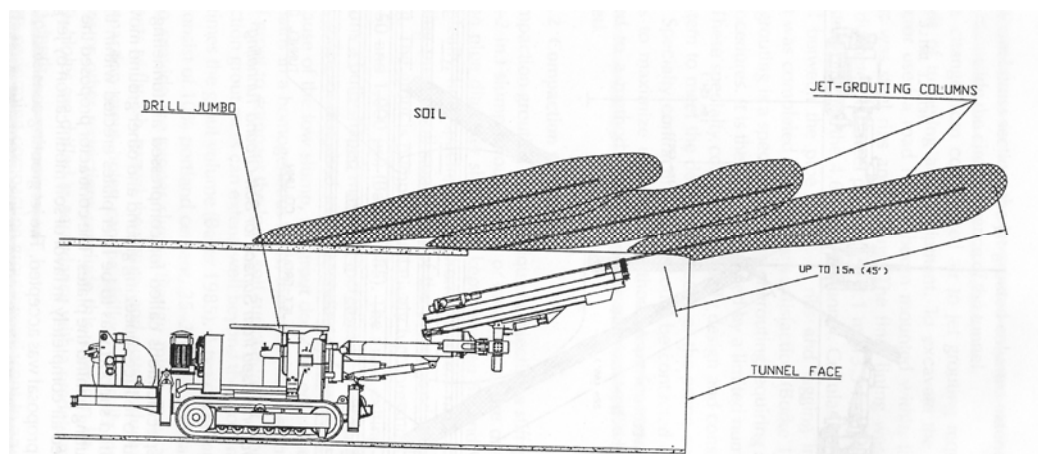
Grout volume reflects the total quantity of grout required to fill the joints and fissures in rock. There are no means at present to measure the rock void volume. Only the Lugeon units, the ground water outflow, weathering grade and joint spacing of the rock mass will provide some information about it.

Generally, it is assumed that the grout volume is equal to 5% to 10% of the rock mass volume to be grouted.

The grout hole pattern shall be in uniform grid or spacing of 1m to 5m. Its final layout should suit the geometric shape of the grout curtain or plug required. For grouting inside a tunnel under excavation, as a rule of thumb derived from numerous experiences, when grout cover all around the tunnel periphery is needed, grouting in holes not more than 2.5m to 3m apart at the far end, in drill holes not more than 20m to 25m long.

5.1.3 Construction

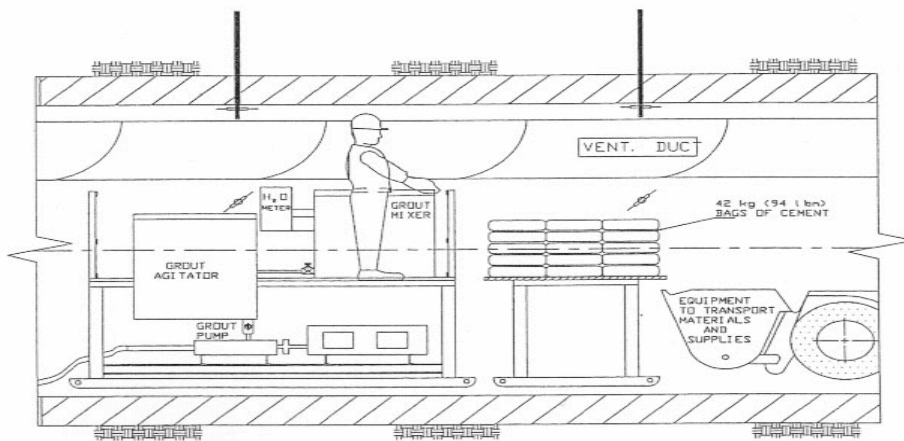
Either the DTH Hammer Percussion Drilling Method or the Top Hammer Drilling Method is deployed to form the grout holes. Sometimes Rotary Coring Method is also used, but is not cost effective. The grout hole diameter is normally from 32mm to 150mm. For grout holes on the tunnel face, a Jumbo drilling rig is the most suitable rig for the job.



Jumbo Drill Rig

The grouting unit consists of a mixer, an agitator, a grout pump and grouting recorder. Refer the following diagram for typical grouting unit arrangement details inside a tunnel. The packer used shall be a mechanical packer for shallow holes and a pneumatic inflatable packer for depth greater than 5m.

Grouting is carried out in stages of 1m to 5m lengths. Grouting records shall be kept which should include the grouting depth, grout intake, grouting pressure and grouting time in addition to the date, hole number etc.



Grouting Unit Arrangement for Rock Fissure Grouting inside Tunnel

If the rock mass is with high Lugeon unit, it is preferable to inject the grout in stages to prevent the grout from flowing outside the treatment zone.

To have good grouting result, it is recommended to terminate grouting according to minimum grouting pressure attained, not by volume of grout used.

5.1.4 Application

Rock fissure grouting technique has a long history of application in civil engineering. Its main applications are:

1. Sealing rock mass underneath and at ends of dams to prevent seepage or leaking of the reservoirs.
2. Sealing rock mass above and underneath a rock tunnel to prevent water seepage into the excavated tunnel.
3. Cementing fractured rock mass.

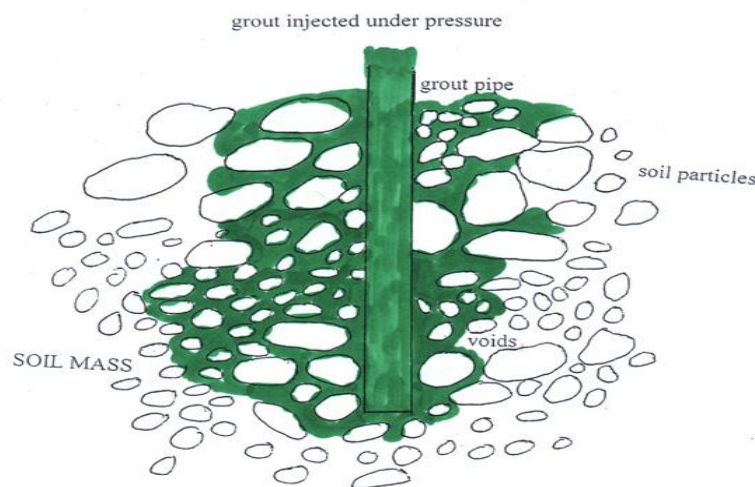
Although Rock Fissure Grouting technique can be used to cemented sugar clubs rock formation, like in slope stability projects, its main application is in the field of water stopping, especially in tunnel excavation project.

5.2 Tube-à- Manchettes (TAM) Grouting

Tube-à-Manchette (TAM) grouting is the use of sleeved perforated pipes in grout holes, soils or completely decomposed rock to allow grout to be injected at close centres vertically, and re-injected, if necessary.

5.2.1 Grouting Mechanism

It is a grouting technique for grouting in soil formation only, with partial or complete displacement of in-filling ground water.



Schematic Diagram of the Impregnation Mechanism for TAM Grouting

The pores/voids in between the soil particles are filled with grout under pressure with partial or complete displacement of in-filling ground water. When the grout has set, the soil mass becomes a matrix of soil particles cemented by the grout. In addition to the sealing purpose, it also changes the property of the soil mass e.g. the strength of the soil mass

The most obvious change in ground property by this treatment method is the reduction of permeability. Ground consolidation is also attained, but the increase in strength is limited. For high strength improvement, it will be very expensive.

5.2.2 Grouting Scheme Design Considerations

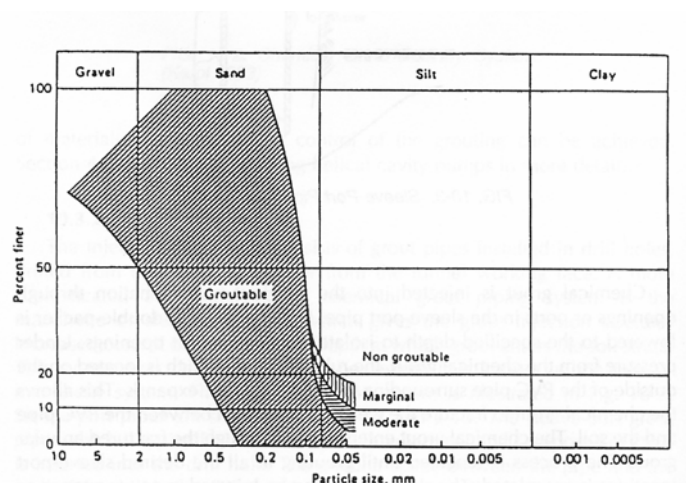
Similar to the Rock Fissure Grouting technique, there are also several considerations that need to be considered in the design of a grouting scheme based on this impregnation grouting mechanism.

Ground investigation is required to define the soil strata and its related ground water regime to be grouted. In each soil strata, soil samples shall be recovered for laboratory

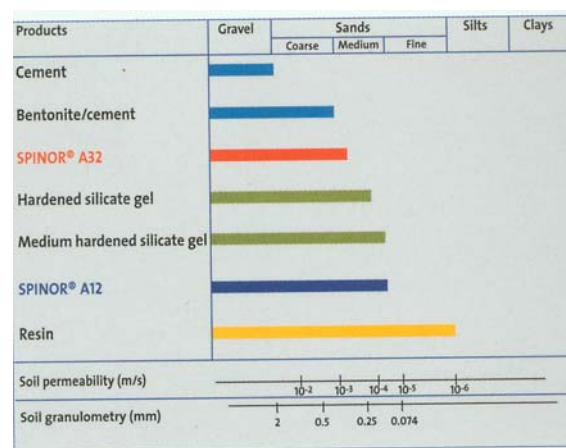
testing to find the PSD, porosity, dry density, pH value, plastic and liquid index. If consolidation is the aim of the grouting work, the shear strength is also required. In-situ permeability tests shall also be performed to find the permeability of the soil mass to be grouted.

It is impossible to measure the actual size of the soil particle voids due to its very tiny dimensions, talking about sizes in microns. There are two methods to measure indirectly the soil void opening. One method is to measure the permeability of the soil to be grouted either by the Falling and Rising Permeability Test or the Constant Head Permeability Test, as the permeability of the soil mass is proportional to its void opening.

The other common method used is to plot the Particle Size Distribution (PSD) Curves from representative soil samples of the soil mass to be grouted. The obtained PSD envelope will provide valuable information about the dominant size of the soil particles, which is proportional to the void opening in between the soil particles. Based on the permeability test results and the PSD envelope, one can decide if the soil mass is groutable or not and which kind of grout is to be used.



Groutability Based on Grain-Size Distribution (Karol 1983)



Limits of Grout Penetrability (SPINOR A12 Catalogue)

Grout property consideration relates to the purpose of the grouting scheme. It can be aimed at improving waterproof of the soil mass for later on excavation work or aimed at improving the consolidation of the soil mass to stabilize the excavation face. Sometimes, both considerations are required.

The mix proportions of the sleeve grout is same as that used for rock fissure grouting and is not repeated here again. The chemical grout is comprised of sodium silicate solution mixed with an organic ester hardener. Sometimes, sodium bicarbonate is used as the hardener because of its much lower cost per meter cube of grout. But, the hardened grout is soft in nature and is good for water stopping only. The setting time is set to be about 20 to 50 minutes. The typical mix proportions of the chemical grout is as follows:

Sodium Silicate 35-37° Baume	286 litre
Water	666 litre
Hardener 600C	48 litre

The silicate content can be increased if it is required to have a higher strength chemical grout to achieve good consolidation purpose. In fact, sodium silicate-based grouts can develop unconfined compressive strengths on the order of 70 kPa to 3500 kPa (Rhone-Poulenc handbook), depending primarily on silicate content and set time, but also on reactant, grain size, and other factors. Normally, silicate based chemical grout is good for water stopping. For strength consideration, the cost per meter cube of grout is tremendous high and is seldom used.

High grouting pressure is preferable in order to have good penetration of chemical grout into the soil. It is quite common in Hong Kong for the Engineer to specify in the contract that the refusal grouting pressure shall be slightly over the overburden pressure plus 100kPa or 20kPa per meter depth. It is too conservative and will not have a good grouting result.

In fact, there are two different types of grouting pressure to consider. One is the pressure recorded while the grout is flowing. Its magnitude is usually much higher if one takes into account all the hydraulic losses need to be overcome. The other grouting pressure is the pressure recorded when the grout is not flowing i.e. the grouting lock-off pressure. Refer the third last paragraph of the Section 4.4 for more information.

From the previous practice in Hong Kong, the injecting pressure can be as high as 2.5MPa and the damage to the ground is quite limited (Barton & Quadus 2003). With regard to the grouting lock-off pressure, it can be set as follows: -

Grouting lock-off pressure = Overburden pressure + 100kPa (holding time = 5 min.)

Grout volume reflects the total quantity of grout required to fill the voids in between the soil particles. An important parameter in determining the volume of chemical grout to be injected is the porosity of soil. Typical groutable soils have porosities ranging from 25% - 50%. The actual porosity is governed by the grain size distribution and soil density.

Grout volume can be estimated once the hole pattern is fixed. The volume of grout required is given by the following formula (Henn 1996).

$$V_g = V_z (\eta F) (1+L) \quad , \text{ where}$$

V_g = liquid volume of grout

V_z = total volume of treated zone

η = soil porosity

F = void filling factor

L = grout loss factor beyond the boundary

The void-filling factor, which actually represents the effective porosity of soil ranges from 0.85 to 1.0 and is generally governed by the pore size and percentage of fines. The grout loss factor ranges from 0.05 to 0.15 and is governed by the grout zone geometry, number of injection points and variability in ground conditions. In short, the grout loss factor is just an assumed wastage percentage of grout injected.

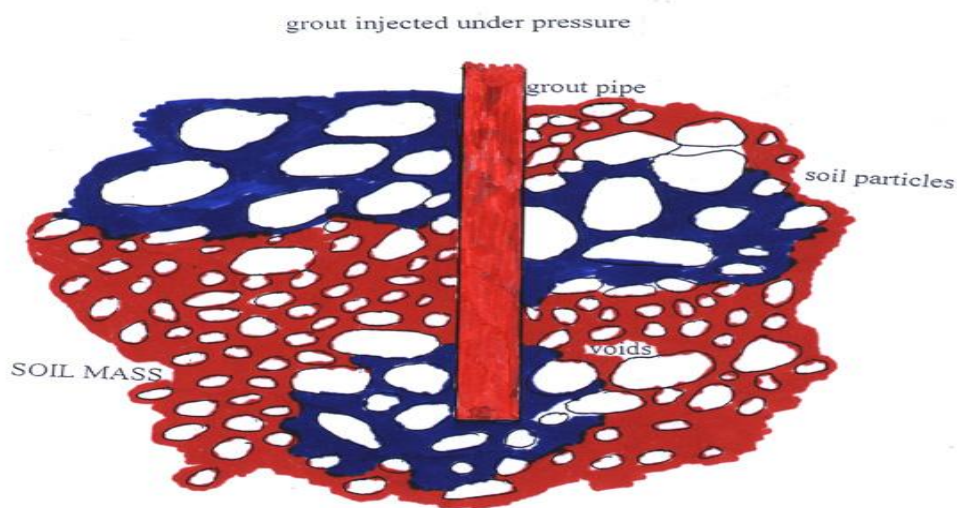
The grout pipes are made of PVC or steel pipes with rubber sleeves (tube-à-manchettes) at 0.33m center to center, sometimes the sleeve is at one meter spacing. It is generally assumed that flow from grout injection ports will be radial and uniform. Grout pipes are spaced in a pattern that provides for primary, secondary, and sometimes tertiary injection. For permanent or important grouting work, split spacing is adopted. Spacing of grout pipes generally ranges from 0.5m to 2.5m

5.2.3 Construction

This grouting technique has two phases, namely the cement bentonite grouting phase and the chemical grouting phase. Hence, the grouting mechanism of this technique is best described with two phases. Refer the following schematic diagrams for details.



Grouting Mechanism of the Cement Bentonite Grouting Phase



Grouting Mechanism of the Chemical Grouting Phase

In the cement bentonite grouting phase, the grout fills up the relict joints of the soil mass and the large voids between the soil particles. In the chemical grouting phase, the chemical grout, which is a chemical solution penetrates and fills up the voids between the soils particles. All the infilling ground water is expelled. When the grout has set, the soil mass becomes a matrix of soil and grout and possess properties quite different from its original soil mass.

The cement bentonite grout with the same mix proportion as that used for the Rock Fissure grouting mentioned in the previous section is injected at 1m stages for each grout pipe from bottom upwards first. After setting of the cement bentonite grout, chemical grout is injected at 0.33m stages from bottom upward as well for each grout pipe. Grouting records are kept as that for the rock fissure grouting.

When the pre-determined grout take per stage has been injected with pressure not reaching the refusal pressure, grouting shall be stopped. Re-grouting is performed when the grout has set. After grouting, all grout pipes shall be washed and cleaned for re-grouting if necessary after review of the overall grouting pressure profiles.

For good grouting result, it is important to terminate grouting according to grouting pressure, not grouting volume. In the following, a typical grouting termination criterion commonly put in the particular specification is quoted for reference.

“3.1.6 Grouting shall be stopped if one of the following criteria is met:

- (i) Grouting pressure exceeds 5 kg / cm^2 or twice the effective overburden pressure, whichever is greater.*
- (ii) Intake of grout reaches 100 litre per meter of the grouting section.*

3.1.7 In the event that criterion (ii) is met at a pressure lower than the above criterion (i), re-grout the grouting section to achieve criterion (i) when the injected grout has set.....”

As has been illustrated in the chemical grouting mechanism model, water is expelled and displaced from the voids of the soil mass, it is important to perform chemical grouting from inside outwards in order to let the infilling ground water to dissipate away during the grouting operation.

Good sleeve grouting is vital to the result of the grouting work for this grouting technique and must be done properly. In order to have a good grouting result, it is also required to provide a minimum 2m thick overburden cover.

As there is quite a large volume of grout to be injected into the ground, it is necessary to monitor the ground heaving during the grouting operation. The chemical grout is classified as pollutant in certain countries; the mix proportions should be checked carefully to ensure that 100% neutralization has taken place.

With the development of ultra-fine cement (with fineness 12000cm² / gm), it is claimed that it can replaced the sodium silicate chemical grout completely. Refer the supplier manual for more details.

SPINOR A12 is an ultra-fine blast furnace slag binder with a grain size distribution finer than 12 μ m. Combined with a dispersing agent, SPINOR A12 exceeds the groutability of conventional bentonite cement suspensions, permeating low porosity soils with permeability coefficient up to 1×10^{-4} .

However, one should be cautiously to adopt it with full trial grouting test to verify its claimed properties.

The Top Hammer Overburden Drilling Method is the most common method to form the TAM grout holes. The grout pipes are normally installed at 1.2m grids in holes with the same pattern. Sleeve grout is used to seal the gap between the grout pipe and the hole. Hole pattern and depth shall follow the geometrical shape of the soil mass to be grouted. In case of difficult terrain, obstructions or access, fanning out technique is used.

5.2.4 Application

Main applications of the TAM grouting technique are: -

1. Sealing soil mass above and underneath a tunnel excavated in soil under compressed air condition.
2. Sealing soil mass behind the soldier pile wall, pipe pile wall etc.
3. Sealing “windows” in cofferdams

4. Consolidation of loose soil mass (cohesionless granular sand)
5. Sealing underlying soil of dams

Before going to discuss more details about the application of this grouting technique, let us discuss why the TAM grouting method is the most efficient grouting method for grouting soil, especially for water stopping purpose.

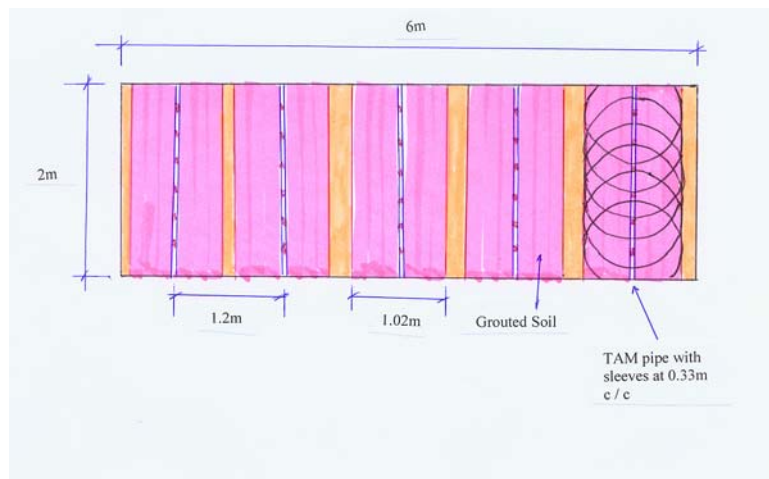
According to the trial test between grouting with the Drill Tool Method and the TAM Method (Sergio et al 1994), the test result has shown that the TAM method can reduce water inflow by 90% when compared with that through Drill Tool Method, which can only achieve 25% reduction.

The following figure represents a submerged excavation soil face area 6m x 2m. Assume that the horizontal permeability of the soil is 5×10^{-5} m/s and ground water inflow into the excavation is evenly distributed for the whole surface and at constant flow rate. For simplicity, complex ground water flow relationship is ignored.

The total ground water inflow into the excavation = $6\text{m} \times 2\text{m} \times 5 \times 10^{-5}$ m/s
 $= 6 \times 10^{-4}$ m³/s.

A grout curtain is installed by TAM method with grout pipes spaced at 1.2m c/c. The rubber sleeves are at 0.33m c/c. The soil porosity is assumed to be 30%. According to the formula $V_g = V_z (\eta F) (1 + L)$, the predetermined grout injection volume per rubber sleeve is 134 litre with $F = 0.85$ and $L = 0.05$.

Assume that all required grout injection volume is achieved. Because of the presence of fines and ineffective porosity, the effective grouting spread radius is only 85% that of the theoretical value 0.6m. Refer to the following grout curtain sketch for details.



TAM Grout Curtain Model

The cross sectional area not covered by the spheres

$$= (1.2\text{m} - 2 \times 85\% \times 0.6\text{m}) \times 5 \times 2\text{m} = 1.8\text{m}^2$$

As all the voids between the soil particles within a sphere are filled with chemical grout, it is reasonable to assume that the permeability of the treated spheres of soil = 0.

The water inflow of the excavation with grout curtain

$$= 1.8\text{m}^2 \times 5 \times 10^{-5} \text{ m/s} = 0.00009 \text{ m}^3 / \text{s}$$

Reduction of ground water inflow into the excavation

$$= (1 - 0.00009 / 0.0006) \times 100\%$$

$$= 85\%$$

The calculation of this grout curtain model has shown that it matches quite well with Sergio's trial grouting test result.

In practical, the hole spacing is 1m c/c with overlapping of treatment for each grout pipe if a single line grout hole pattern is applied. In case of excessive ground water inflow is expected, another line of grout holes with the same spacing is added. The distance between the two lines of grout holes is 0.8m and the grout holes are staggered with each other.

If the same reasoning is applied and assume linear relationship of all the controlling factors, the expected reduction in ground water inflow will be a further 85% on the reduced quantity of inflow from the first layer i.e. $15\% \times 0.00009 = 1.35 \times 10^{-5} \text{ m}^3 / \text{s}$.

$$\text{Reduction of ground water inflow percentage} = (1 - 0.0000135 / 0.0006) \times 100\% = 98\%$$

The equivalent permeability of the grout curtain

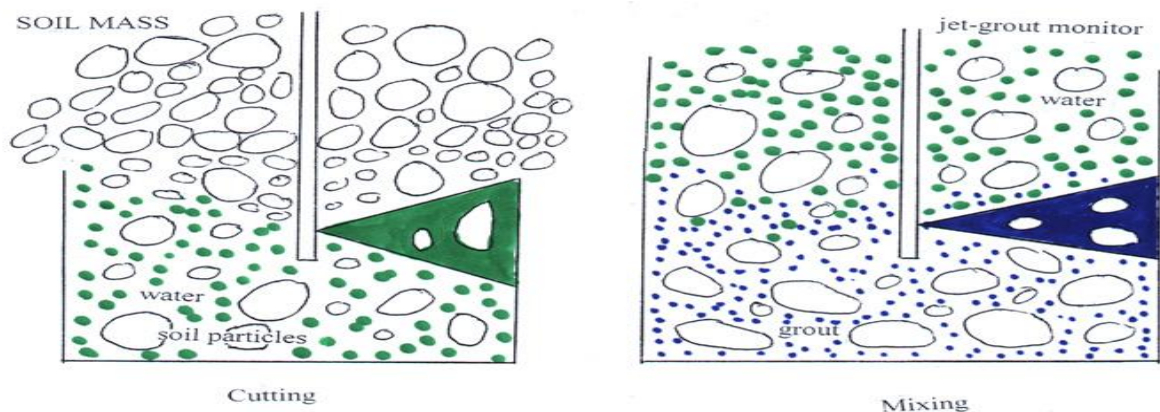
$$= 0.0000135 / (6 \times 2) = 1.13 \times 10^{-6} \text{ m/s} \Rightarrow 44 \text{ times reduction in the soil permeability.}$$

Normally, with the TAM grouting technique, it is possible to reduce the soil permeability a hundred times i.e. from 10^{-5} m/s to 10^{-7} m/s .

5.3 Jet grouting

Jet grouting is a grout injection that cuts and mixes the soil to be treated with cement or cementitious grout.

5.3.1 Grouting Mechanism



Schematic Diagram of Cut and Mix Mechanism for Jet Grouting

With regard to the CUT and MIX grouting mechanism, the soil particles are cut by the grout jetting under high pressure and mixed with it to form a matrix. When the grout set, the matrix is not only impermeable, but also possesses some kind of strength. The strength of the matrix depends on the grout strength and the degree of soil replacement.

5.3.2 Grouting Scheme Design Considerations

Ground investigation is required to define the soil property. The main information required is the shear strength or the resistance profile of the soil mass to be grouted. For example, for completely decomposed volcanic and igneous rocks, when the SPT N value is greater than 50, the soil mass is normally classified as not suitable for jet grouting.

The other important soil property to consider is the cobble / boulder content. The presence of cobble / boulder will cause 'Shadowing' effect on cutting and mixing which is not desirable. If the quantity of cobble/boulder is in large amount, the soil mass is also not suitable for jet grouting.

Grout property, especially the strength property relates to the final design strength of the mixed soil mass. The final strength of the mixed soil mass relates to the purpose of the grouting and the requirement is different for different schemes. This implies

that a trial mix is necessary to find the optimal grout mix proportions for the grouting scheme.

Normally, pure cement grout is used for jet grouting to strengthen the ground. The water cement ratio used is 1 generally. The compressive strength of soil cement mix ranges from 2 MPa to 25 MPa and is determined by the cement content and the remaining portion of the soil in the soil cement mass.

For water sealing purpose, bentonite is usually added to the cement grout to achieve better resistance to ground water ingress.

Cutting time is important in the design of a jet grouting scheme. The longer the cutting time is, the more the original soil mass be displaced and the larger the grout column diameter.

Mixing time dictates the extent of mixing of the grout and the soil mass. The longer the mixing time is, the more thorough the mixing effect. One point to note is that prolonged mixing will eventually displace all the soil mass and replace it with the grout.

In the design of the jet grouting scheme, trial jet grouting test is the most common method to confirm the parameters of a jet grouting scheme. In such a test, several jet grout columns are constructed using different sets of parameters. Then the constructed jet columns are exposed or cored through with a drill rig to measure its diameter achieved and the strength of the column material. The set of parameters that produces column closest to the design requirement is adopted for construction. Refer the following for a set of parameters used to construct jet columns for a project in Hong Kong.

Parameter	Water Pre-jetting	Cement Grout Jetting
Nozzle	2 no. x 3mm	2 no. x 3mm
Air Pressure	12 bar	12 bar
RPM	15	15
Jet Pressure	370 bar	450 bar
Up-lift Speed	60 cm / min	14 cm / min
Flow Rate	230 litre / min	207 litre / min
Water/Cement Ratio	-	1

Table 3: Set of Jet Grouting Parameters Used in a Project in Hong Kong

5.3.3 Construction

The grouting unit consists of a jet grouting rig, a jet grout pump, an automatic grout batching unit, a jet grout recorder, a water pump and a high-pressure air compressor. Refer the typical jet grouting setting up sketch.

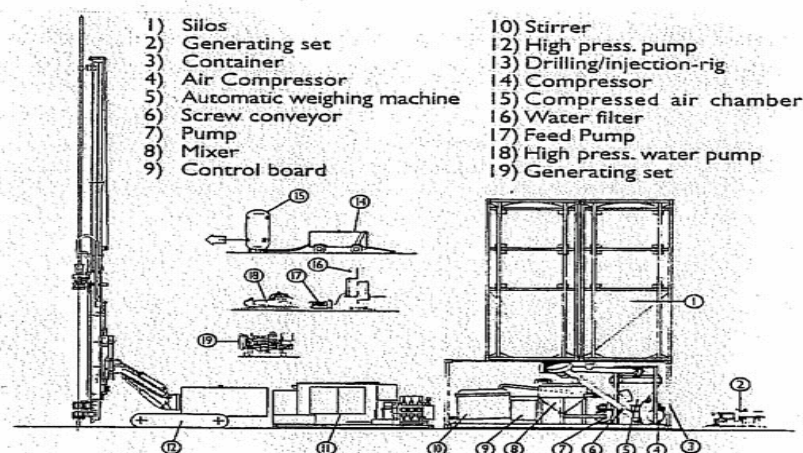
A spoil handling system should also be designed, as there will be a lot of spoils coming up from the hole during the jet grouting operation.

Drill rods equipped with jet nozzle holder, also called “monitor” in some literatures and drill bit are used to drill the jet grouting hole down to the required depth. Normally the jet grout mixture is used as the flushing medium to stabilize the drill hole during the drilling operation. In masonry and concrete, special drilling bits or tools like the water hammer are used.

The dissolution of the grain texture with a powerful fluid jet starts at the lower end of the jet grout column. The excess water soil cement mixture is removed to the surface through the annular space between the drill rod and drill hole wall. The pre-selected grouting parameters are constantly monitored.

After that, the grout is injected under pressure simultaneously with the cutting of the soil. The turbulences caused by the jetting result in the uniform mixing of the grout and soil within the treatment zone. Until the grout in the jet grout column starts setting hydrostatic pressure in the drill hole is kept by backfilling grout into the hole from time to time.

To do a good jet grouting work, the cutting and mixing time have to be controlled accurately in addition to the consistency in the grout mix proportions, jetting pressure and monitoring of grouting spoil density. Finally, it is very important to monitor the verticality of the jet columns. Excessive deviation may cause problem to the overall design of the jet grout structure.



A Typical Jet Grouting Setting Up

5.3.4 Application

The jet grouting technique is developed in the 1960s. However, because of its unique properties, it is becoming quite popular in the civil engineering works. Its main applications are: -

1. Grouting of clay / silt soils which is not suitable for TAM grouting technique.
2. Jet grout wall and roof are used to reinforce tunnel portal excavation works.
3. Sealing of windows of coffer dams
4. Used as jet grout raft to reinforce cofferdam to limit its deflection and thus decrease the settlement caused by the excavation works.

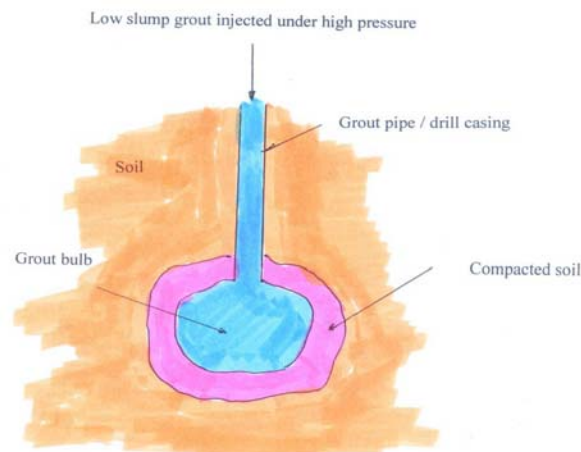
Both TAM grouting technique and the Jet grouting technique can increase the strength of the soil. However, when compared, the jet grouting technique can improve the ground strength much more efficient than the TAM grouting technique. It is more reliable as well as cheaper in cost.

Of course, if one has to deal with water stopping in granular soil, the TAM technique is more superior as it is much cheaper than by the jet grouting technique. In the following example, the advantage of using the jet grouting technique to improve the ground strength is addressed.

5.4 Compaction Grouting

Compaction grouting is a single-stage grouting with high strength mortar to the ground to create a grout-bulb at the end of drill pipe.

5.4.1 Grouting Mechanism



Schematic Diagram of the Displacement Mechanism for Compaction Grouting

A stiff grout with a very low slump is injected under relatively high pressure through pipes or casings into soil. The grout exiting the bottom of the pipe forms a bulb-shaped mass that increases in volume. Displacement of the soil is produced by the weight of the overburden pushing back against the expanding grout bulb. Thus it densifies the soft, loose, or disturbed soil surrounding the mass.

It can also be used to alleviate settlement problem during the excavation of tunnel or deep basement as the hardened bulb-shaped grout will induce an increase in the soil volume strain to the soil strata and cause heaving of ground at the ground surface.

5.4.2 Grouting Scheme Design Consideration

Ground investigation work is required to have a thorough analysis of the soil to be treated. Normally, disturbed samples are required to distinct the various soil strata. SPTs are performed to know the relative resistance of the soil. Undisturbed soil samples are recovered for laboratory testing to find the index properties and the stress strain response of the soil. In-situ tests like Cone penetration test (CPT), Vane Shear Test and Pressuremeter test (PMT) are carried out to know the in-situ modulus of the soil. All the above-mentioned geotechnical data are required for the determination of the grouting parameters of a compaction grouting scheme, which is also purpose dependent.

The grout used is thick cement based grout with very low slump, less than 50mm. Sometimes fillers are added in to reduce the cost as well as to increase the viscosity of the grout.

Because of the low slump, the grout does not enter the pores of the soil but remains in a homogeneous mass, thus allowing the controlled displacement of grout to compact the loose soil surrounding it.

A typical compaction grout mix might consist of 10% cement, 25-30% silt and sand and sufficient water to provide the proper slump.

The grouting pressure used should be high enough to fracture the ground. The grout is pumped at relatively high pressure between 1 and 7 MPa.

To alleviate ground settlement caused by basement or tunnel excavation work, grout injection volume is normally predetermined by means of a finite element model that we shall discuss in more detail after. However actual grout quantity will depend on the actual result achieved.

For soil densification purpose, the grout volume used has to be controlled strictly according to the result required; otherwise it may fracture the ground and producing undesirable result. Normally, it will not exceed by 5% of the volume of the ground to be treated (Soletanche 1988).

Typically, hole spacing ranges from 1.5m to 6.0m center to center depending on the soil conditions of the project and desired results of the grouting. Compaction grout holes can be drilled vertically or, where existing structures or other site constraints are present, inclined holes can be drilled. Holes are drilled according to a predetermined split spacing pattern to a required depth. The grout pipe can be the drill casing or a steel pipe with nominal diameter 75mm.

5.4.3 Construction

As this grouting technique will involve large displacement of ground, it is important to assess the stability of the structure and determine if or not its stability is affected by the grouting work. It is required to monitor the structure during the grouting operation. Any unexpected movement of the structure has to be analyzed to assess the extra stress imposed on the structure due to the movement and its likely effects.

A steel casing, minimum 75mm is drilled to the required depth. A thick, mortar-like cementitious mixture less than 50mm slump is pumped at pressure 7MPa contained within the casing to form a cohesive bulb.

The grouting bulb is expanded to 33cm diameter by displacement of the adjacent soil at the lower tip of the casing while a calculated and measured volume of grout is maintained. Depending on the extent of treatment, the grouting tube maybe raised 33cm and the geotechnical compaction process repeated. And thus a grout column is

formed instead of a grout bulb. This construction method is usually adopted for lateral soil densification work.

Usually, compaction is applied in stages beginning at the lowest point of drilled shaft and working upward through the ground. On very shallow compaction grouting applications, it can be injected from top down. This method compacts the upper portion of the ground first so that it becomes a dense cap to help contain the expanding grout at the lower levels. When applied in a grid style layout, the pressure treated soil underneath the foundation has a greater uniformity throughout its entire mass, which gives maximum soil stabilization and provides solid foundation support.

5.4.4 Application

Compaction grouting is a soil and foundation support improvement system that increases the bearing capacity of soils. A major advantage of using compaction grouting is that its maximum peak effect is realized in the weakest or softest strata of the infrastructure support.

Its main applications are as follows:

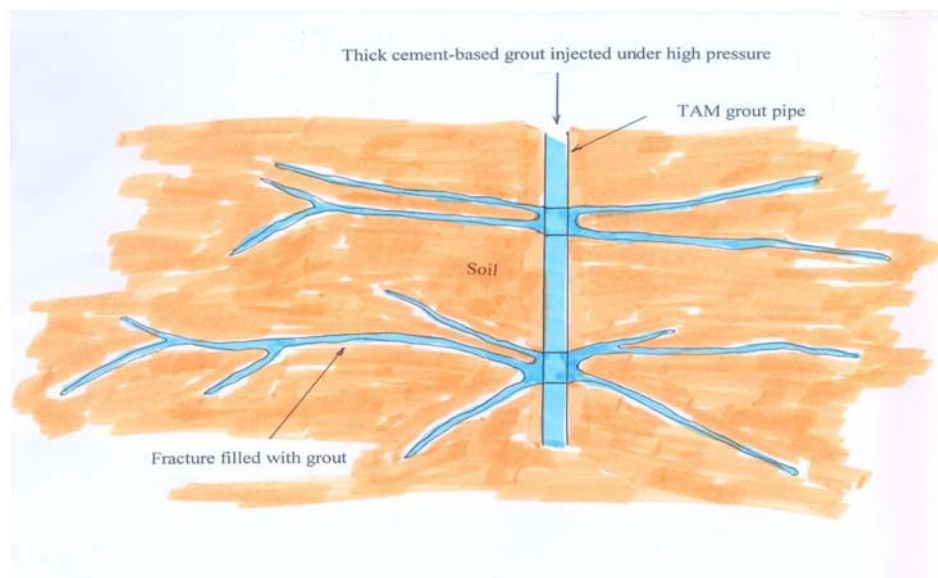
- a. Lateral static densification of soils.
- b. Lifting and re-leveling roads, bridges, and other existing structures
- c. Blocking of flow-path of viscous liquids through stratum layers and rock cracks, voids, and fractures
- d. Construction of underpinning
- e. The remediation of sinkholes

The example given in the following section will confine to the application of compaction grouting technique in settlement control. The aim is to have an apple-to-apple comparison with the compensation grouting technique applied in the control of settlement as well.

5.5 Compensation Grouting

Compensation grouting is a grout injection that can 'compensate' for stress relief and associated ground settlement (K.Soga et al 1999).

5.5.1 Grouting Mechanism



Schematic Diagram of the Hydro-Fracture Mechanism for Soil Grouting

Grout is injected through grout pipes, which are usually TAM grout pipes, under high pressure into the soil. Fractures in soil are created which are then filled with grout. The fractures filled with grout will follow the plane with the minor principle stress and formed in layers. The increase in volume will compact disturbed soil surrounding the mass, will compensate settlement caused by tunnel excavation works and can be used to lift up settle structures.

5.5.2 Grouting Scheme Design Consideration

Ground investigation work is required to have a thorough analysis of the soil to be treated. Normally, disturbed samples are required to distinct the various soil strata. SPTs are performed to know the relative resistance of the soil. Undisturbed soil samples are recovered for laboratory testing to find the index properties and the stress strain response of the soil. In-situ tests like Cone penetration test (CPT), Vane Shear Test and Pressuremeter test (PMT) are carried out to know the in-situ modulus of the soil. All the above-mentioned geotechnical data are required for the determination of the grouting parameters of a compensation grouting scheme.

Grout used is normally a stable, fluid and cement-based grout. However the water cement ratio is usually varied to suit different stages of compensation grouting. Below is the grout mix proportions used in a compensation grouting scheme in different stages of the grouting work.

a. Sleeve Grout

– Used to seal the TAM grout pipes in holes.

For 1 m³ of grout,

Bentonite	35 kg
Cement	250 kg
Water	910 litre

b. Ground Conditioning and Tightening Stage Grout

– Used for compaction of soil, standard viscosity and strength.

For 1 m³ of grout,

Bentonite	35 kg
Cement	350 kg
Water	875 litre

c. Hydro-Fracturing Stage Grout

– Used for the main grouting work, increased viscosity and strength.

For 1 m³ of grout,

Bentonite	35 kg
Cement	450 kg
Water	840 litre

The type of low slump grout used for compaction grouting is too thick for the TAM injection method used.

The grouting pressure used is much higher than the normal TAM grouting technique in order to fracture the ground hydraulically. It may go up to 4 MPa. Similar to the grout mix proportions, the grouting pressure will be varied during different stages of the compensation grouting scheme. It will start with a pressure slightly above the overburden pressure and then increase as the grout becoming thicker and the ground

more compacted. When compared with the compaction grouting method, the grouting pressure is much lower.

The grout volume injected depends on the grouting purpose of the grouting scheme. For settlement compensation, it will relate to the degree of heaving required while for structure lifting, the height of the structure to be lifted.

In designing a compensation grouting scheme, 2D finite element model is usually used to estimate the indicative grout volume to be injected based on the amount of heaving and lifting required and the soil properties of the different soil strata of the treatment zone concerned. But, the actual quantity will still depend on the result of the initial few stages of grouting.

The grout holes are normally locate right underneath the structure to be lifted or to be compensated in settlement. They are usually installed in soil strata that are near to the source of ground losing or the soil is firm or dense for structure lifting. The grout hole spacing is around 1m apart or 1.5m at the far end of the grout pipes.

The grout holes are normally horizontal in order to give the best grouting result, but inclined holes are used if the site conditions prevent it from drilling horizontal grout holes. Of course the grouting result will be less effective.

Since heave compensation or structure lifting are very sensitive operations, an overlook of something could result in damage of the structure to be lifted or would induce extra stress to existing structure with shallow foundation or nearby earth retaining structures. A serious compensation trial grouting test is preferable in order to establish the stress strain response of the in-situ soil strata.

5.5.3 Construction

TAM grout pipes are installed into the soil formation to be treated and the annular space between the hole and sleeve pipe sealed with a stiff cement-bentonite grout, same as the TAM grout pipe installation for the TAM grouting.

A grout hose equipped with a double packer is inserted into the grout pipe. The packer seals the grout pipe on either sides of a rubber sleeve, thus allowing the grouting of each single rubber sleeve along the section to be treated.

The sleeves along the grout pipe may be grouted once or several times according to the technical requirements. The grout quantity, the maximum grouting pressure and, in case of repeated grouting the setting times are maintained according to instructions. TAM grout pipes can remain reusable for long periods.

Compensation grouting is usually divided into three stages after grout pipe installation. Initially, the ground is grouted to fill up all the large voids or relict joints, if any. The grout is not thick, similar to that used for rock fissure grouting. The grouting pressure is just slightly over the overburden pressure.

Then the ground is tightened i.e. slightly compacted by the injection of thicker grout with a higher grouting pressure. At this stage, it is required to monitor closely the ground heaving or the uplift of the structure. A limit of 5mm is usually allowed and used as a stopping criterion for this stage of compensation grouting.

The final stage is to compensate the required ground settlement by heaving or the required uplift of the structure. The grout is much thicker and the grouting pressure used is much higher. In order to have a fine control on the heaving, the grout pump should have a fine adjustment on the pumping rate, 4 to 30 L/min with a pressure up to 7 MPa. Normally, the grout pump is hydraulically operated in order to meet such performance specification.

Ground heaving and structure uplift monitoring is a compulsory. Another important point to observe is to inject the grout in an evenly manner. Otherwise, undue heaving or structure uplifts may be resulted and cause extra stress to the structure directly concerned or the nearby structures.

To protect structures against predictable settlements during tunnel construction horizontal grout pipes fans between tunnel roof and the building foundation will be installed from temporary shaft. The building to be protected will be equipped with an electronic measuring system for registration of vertical movements. And compensation grouting is performed whenever necessary as detected by the various monitoring sensors installed.

5.5.4 Application

Where classical grouting techniques for void filling for foundations or restoration of structures is not suitable or the lifting of structures is required, the compensation grouting technique fills the gap within the circle of different grouting techniques.

In the event of excessive settlements, compensation grouting is a suitable process to restore the link between the base of the structure and competent soil formation.

Together with the newly developed measuring and control techniques as well as special observation devices it is possible to lift structures by several decimeters. Lifting of structure is normally performed without restricting their use.

In the following section, the application of the compensation technique in controlling structure settlement is stressed.

Chapter 6. Analysis and Modeling of Grouting

In the previous sections, we discuss about how to design a grouting scheme and how to perform grouting to attain the desired ground properties for each grouting mechanism. However, the problem to what extent grouting has to be carried out in terms of geometric dimensions and degree of improvement of ground properties are still unsolved.

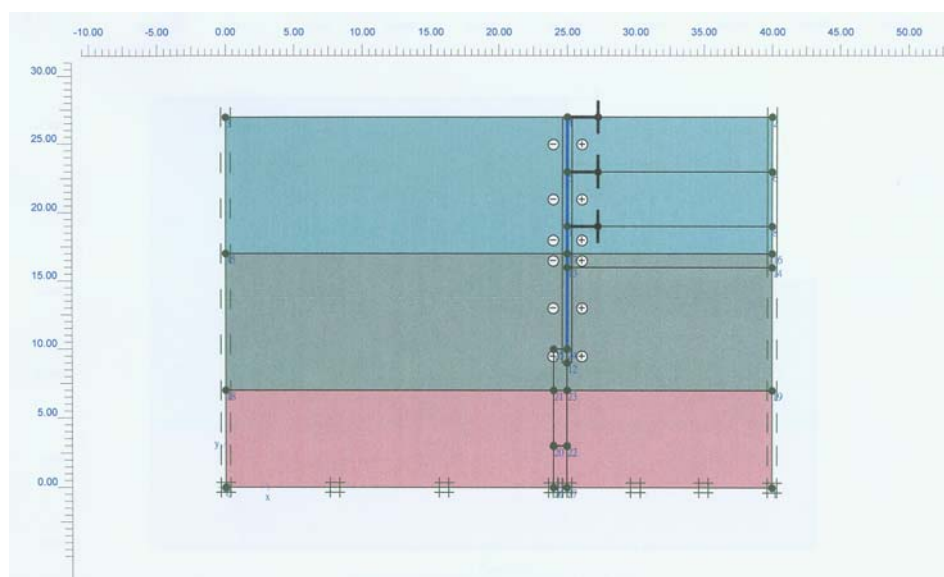
Since it is possible to control the dimensions of grouting zone and the degree of improvement of ground properties, it is possible to use the Finite Element Method to model the grouting and to analyze the optimal settings for the intended grouting works.

6.1 Water Stopping

This example involves the dry construction of an excavation. Steel sheet-pile walls support the excavation. Three layers of struts support the walls at 5m intervals.

The excavation is 30m wide and 11m deep. 17m long steel sheet-pile walls are used to retain the surrounding soil. Three rows of steel struts are used at each wall to support the walls.

The relevant part of the soil consists of three distinct layers. From the ground surface to a depth of 20m are two layers of hydraulic fill, each 10m thick. The top layer is of relatively loose fine sandy soil. The second layer of fill is also fine sandy soil but not so loose in nature. They are more or less homogeneous layers of high permeability coefficients. The ground water level is at 3m below the ground surface. Below the sand layer is the Alluvium layer, a clayey sand layer, which extends to 7m depth. Refer the following geometry model for details.



Geometry Model for 2D Finite Element Analysis

The geometry model is set up according the PLAXIS Reference Manual. Only half of the section is shown, as the excavation is symmetric. The material properties used for the analysis are listed in the following tables.

<u>Parameter</u>	<u>Name</u>	<u>Unit</u>	Hydraulic Fill 1	Hydraulic Fill 2	Alluvium
Material model	Model	-	MC	MC	MC
Type of material behaviour	Type	-	Drained	Drained	Drained
Soil unit weight above p.l.	γ_{unsat}	kN/m ³	16	16	17
Soil unit weight below p.l.	γ_{sat}	kN/m ³	19	19	19
Horizontal permeability	k_x	m/day	8.64	8.64	0.864
Vertical permeability	k_y	m/day	8.64	8.64	0.864
Young's Modulus	E_{ref}	kN/m ²	10000	20000	30000
Poisson's ratio	ν	-	0.3	0.3	0.3
Cohesion	c_{ref}	kN/m ²	0	0	4.0
Friction angle	φ	°	38	38	33
Dilatancy angle	ϕ	°	0	0	0
Interface reduction factor	R_{inter}	-	0.67	0.67	Rigid
Interf. Permeability parameter	Perm.	-	Imperm	Imperm	Neutral

Table 4: Property of Soils and Interfaces

<u>Parameter</u>	<u>Name</u>	<u>Value</u>			<u>Unit</u>
		<u>Strut 1</u>	<u>Strut 2</u>	<u>Strut 3</u>	
Type of behaviour	Material type	Elastic	Elastic	Elastic	-
Normal stiffness	EA	5.6×10^5	6.667×10^5	9.622×10^5	kN
Spacing out of plane	L_s	1.0	1.0	1.0	m
Maximum force	F_{max}	1×10^{15}	1×10^{15}	1×10^{15}	kN

Table 5: Property of the Struts

<u>Parameter</u>	<u>Name</u>	<u>Value</u>	<u>Unit</u>
Type of behaviour	Material type	Elastic	-
Normal stiffness	EA	3.82×10^6	kN/m
Flexural rigidity	EI	3.44×10^4	kNm ² /m
Equivalent thickness	d	0.329	m
Weight	w	2.4	kN/m/m
Poisson's ratio	ν	0.3	-

Table 6: Properties of the steel sheet-pile wall (beam)

In the initial conditions, all structural components are deactivated and a water weight of 10 kN/m³ is used. The initial water pressures are generated on the basis of a ground water level at 3m below ground level. The initial stress field is generated by means of the *K₀-procedure* using the software default K₀-values in all clusters.

Calculation is divided into six phases to simulate the staged construction, as it will be in the actual case. The six phases of construction are:

Phase 1 – Construction of the steel sheet-pile wall and the first level of strut.

Phase 2 – Excavation to the second level of strut. The boundary conditions for the groundwater flow calculation are entered as well.

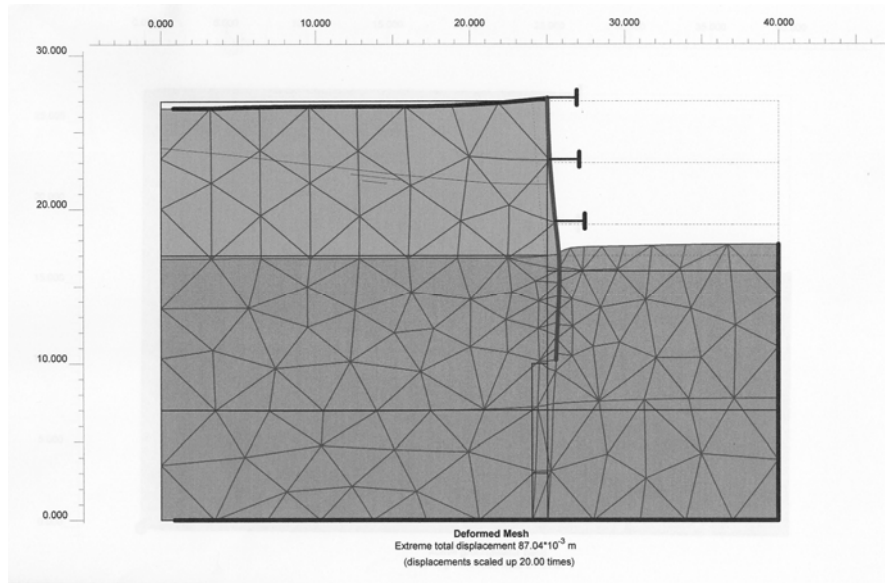
Phase 3 – Construction of the second level of strut.

Phase 4 – Excavation to the third level of strut.

Phase 5 – Construction of the third level of strut.

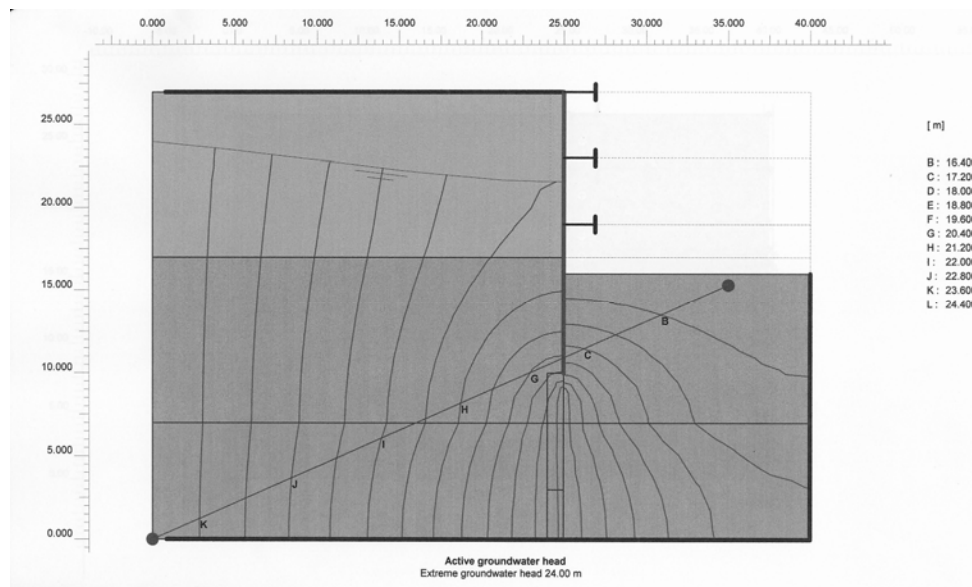
Phase 6 – Excavation to the final formation level.

After the calculation, the extreme total displacement is found to be 87.04mm. Refer the following deformed mesh model for details.



Deformed Mesh Model after Calculation

The ground water inflow into the excavation is $19.10 \text{ m}^3 / \text{day} / \text{m}$ of wall and the ground water drop outside the cofferdam is 2.4m as shown in the following figure.



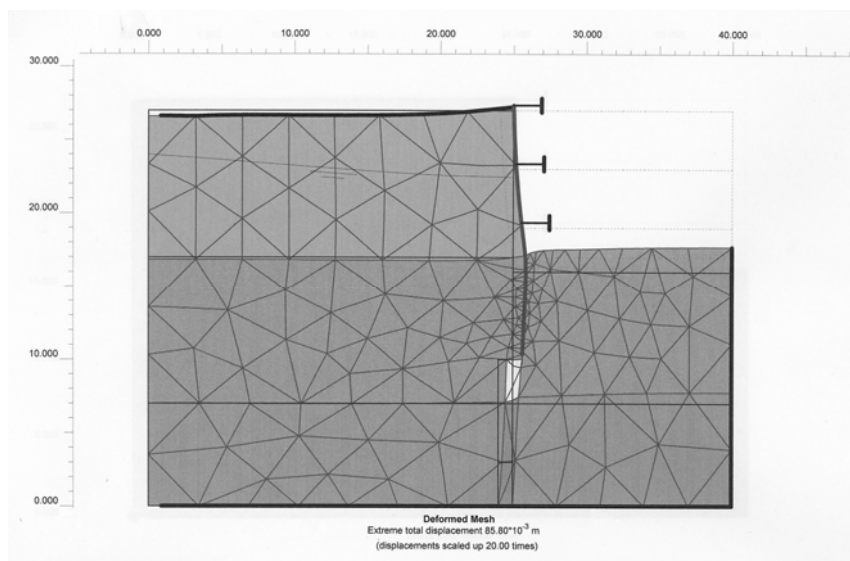
Ground Water Head Contours

Generally, there is restriction on the tolerance of ground water draw down level caused by an excavation work, and the standard is different in different countries. In Hong Kong, it is normally set at 1.5m below base ground water level before excavation. The reason is quite obvious, as excessive ground water level draw down will induce settlement that could cause great consequences.

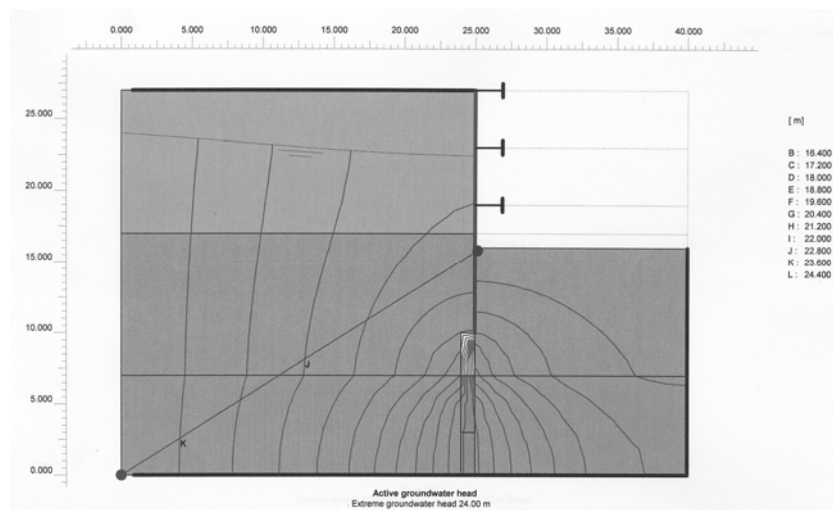
Therefore, it is necessary to construct a grout curtain by the TAM grouting technique, which extends 10m (say) below the steel sheet-pile wall toe level. The thickness of the grout curtain is 1m.

The properties of the grout curtain will be exactly same as the original soil except the permeability. This practice is to simplify the analysis even though grouting may also change the stiffness of the soil.

Set the permeability of the treated soil to be 1×10^{-5} m/s. Even though the permeability of the Hydraulic Fill 2 and the Alluvium are of great different, it is possible to have the same value after grouting. The fact is that, if the same grouting criteria are applied to both types of soil, the same grouting result will be obtained. The only difference is that the soil that is more permeable will have a higher grout intake.



Deformed Mesh Model after Analysis



Ground Water Head Contours after Grout Curtain Installation

The calculation procedures are exactly same as that before grout curtain installation. Refer the above deformed mesh model after analysis.

From the output it can be seen there is a large reduction in water inflow into the excavation. Draw down outside the cofferdam is now 1.6m, just 0.1m to miss the statutory requirement.

The model is used repeatedly using different coefficients of permeability for the analysis. And the results are as presented in the following table.

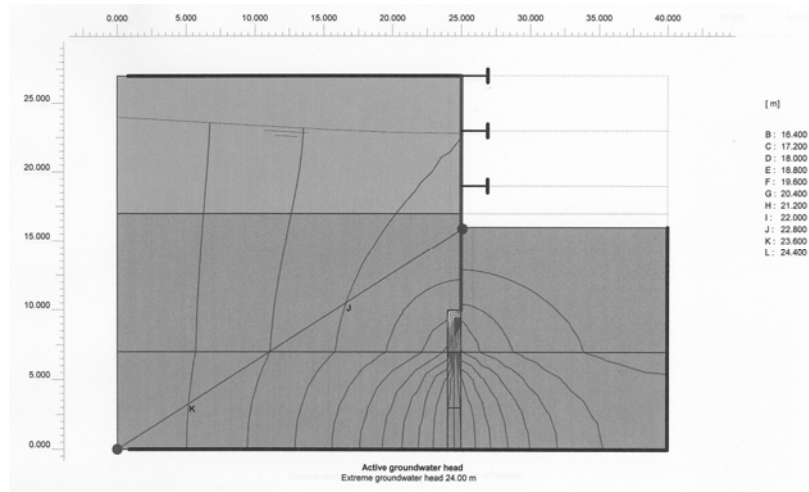
Grout Curtain Permeability	Total Displacement	Water Level Outside Excavation	Water Level Drawdown	Total Discharge Per M of Wall
Without Grout Curtain	87.04mm	21.6m	2.4m	19.10 m ³ /day
1 x 10 ⁻⁵ m/s	85.80mm	22.4m	1.6m	12.92 m ³ /day
5 x 10 ⁻⁶ m/s	85.60mm	22.8m	1.2m	10.21 m ³ /day
1 x 10 ⁻⁶ m/s	84.66mm	23.0m	1.0m	4.94 m ³ /day
5 x 10 ⁻⁷ m/s	84.29mm	24.0m	0.0m	3.38 m ³ /day
1 x 10 ⁻⁷ m/s	83.65mm	24.0m	0.0m	1.57 m ³ /day

Table 7: Effects of Grout Curtain Permeability

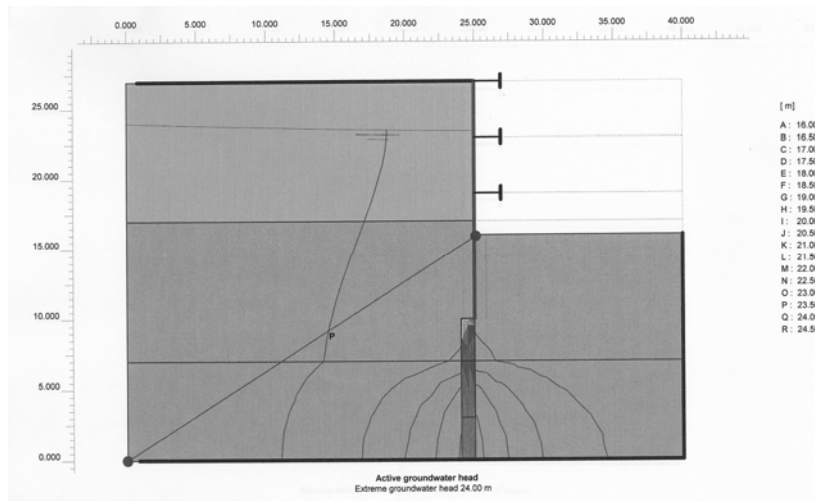
From the table, the trend of decreasing water level drawdown along with the decreasing coefficient of permeability can be seen easily. However, when the permeability has dropped to 1 x 10⁻⁶ m/s, the decreasing rate of the total discharge diminished. In other words, further drop in permeability after 1 x 10⁻⁶ m/s is of little practical value for this model.

To reduce the soil permeability further implies additional grouting volume or/and additional drilling works. And it adds cost to a project and thus is not desirable. Hence, one may conclude that the 1 x 10⁻⁶ m/s grout curtain permeability is the optimal value for this model.

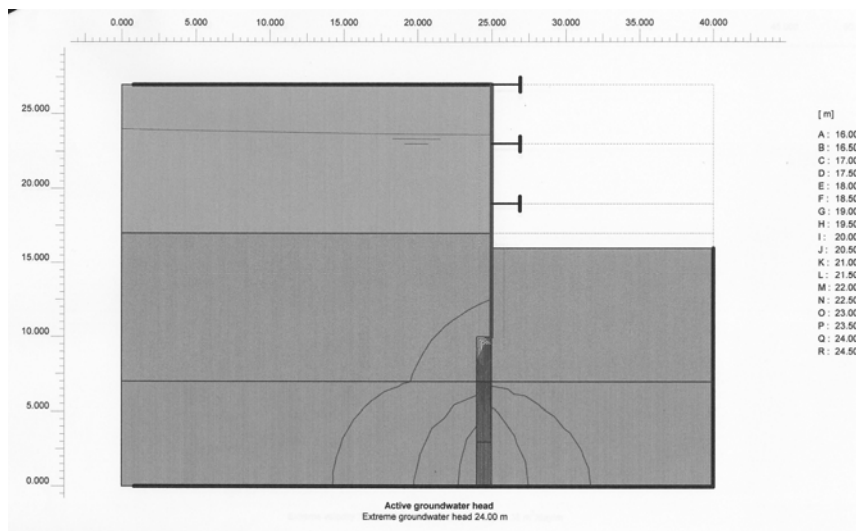
In the following figures, the change in active ground water head for each grout curtain permeability in all the analysis are listed for reference.



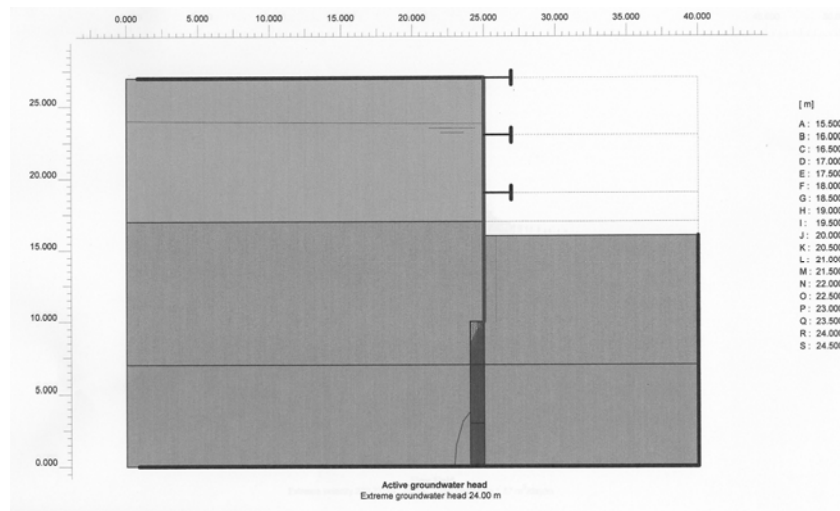
Active Ground Water Head – 5×10^{-6} m/s



Active Ground Water Head – 1×10^{-6} m/s



Active Ground Water Head – 5×10^{-7} m/s



Active Ground Water Head – 1×10^{-7} m/s

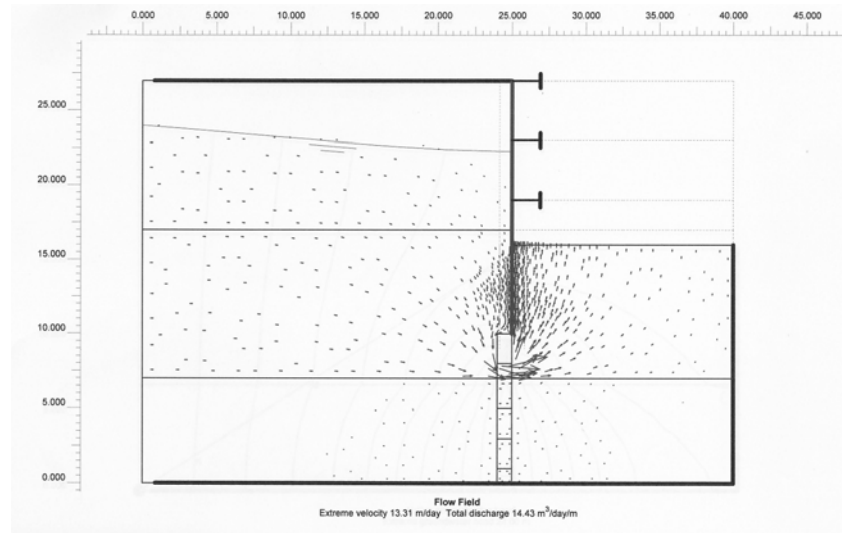
Another problem that has to be solved is to check if or not the 10m-grout curtain length is excessive or inadequate. The cost of the grout curtain is also dependent on its geometric dimensions. The longer the grout curtain, the higher its construction cost.

Again the same model is used to analyze this problem. The permeability is fixed to 1×10^{-7} m/s this time and the grout curtain length is varied. The result of the analysis is as presented in the following table.

Grout Curtain Length	Total Displacement	Outside Water Level	Water Level Drawdown	Total Discharge Per M of Wall
Without Grout Curtain	87.04mm	21.6m	2.4m	19.10 m ³ /day
2m	86.39mm	22.2m	1.8m	14.43 m ³ /day
3m	85.76mm	23.0m	1.0m	7.31 m ³ /day
5m	85.51mm	23.4m	0.6m	4.73 m ³ /day
7m	85.07mm	24.0m	0.0m	3.67 m ³ /day
9m	84.56mm	24.0m	0.0m	2.75 m ³ /day
10m	83.65mm	24.0m	0.0m	1.57 m ³ /day

Table 8: Effects of Grout Curtain Length

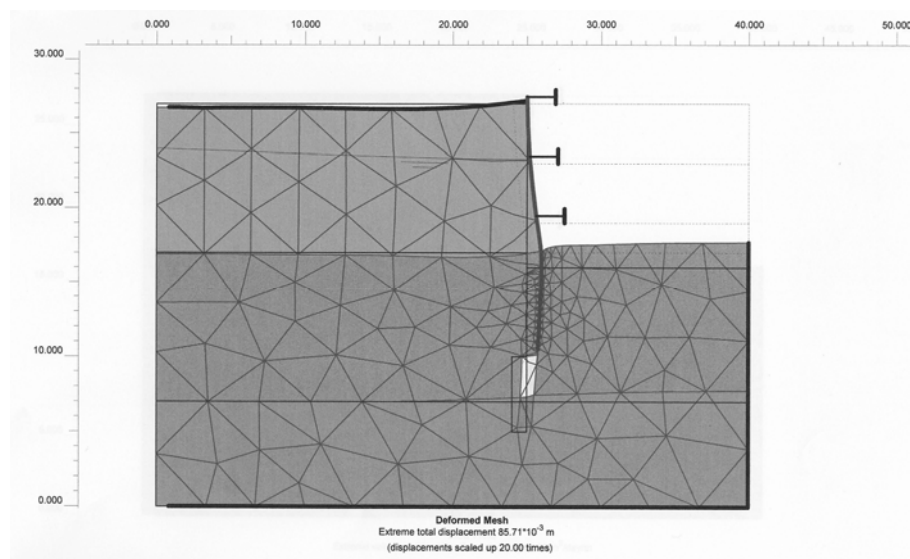
From the table, it is readily seen that there is a dramatic decrease in all significant values when the grout curtain length is extended from 2m to 3m. The main reason is that for a 3m long grout curtain, it sits on top of the Alluvium that is 10 times less in permeability than the Hydraulic Fill 2. It seals effectively the water flow path into excavation. Refer the Flow Field Diagram of the 2m long grout curtain for details.



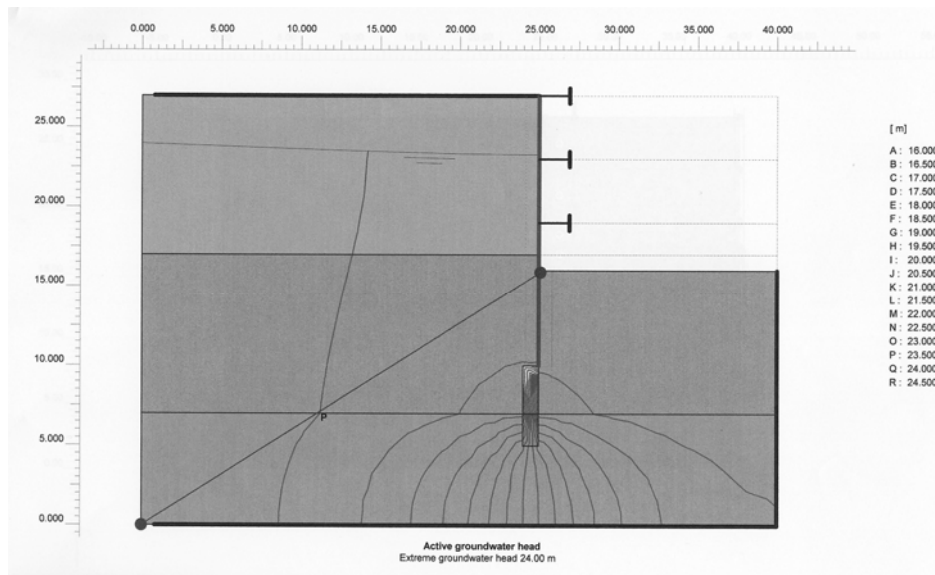
Flow Field of 2m Long Grout Curtain

It is also obvious that there is not much improvement for grout curtain length exceeding 5m. Hence, 5m long grout curtains is the most efficient grout curtain length.

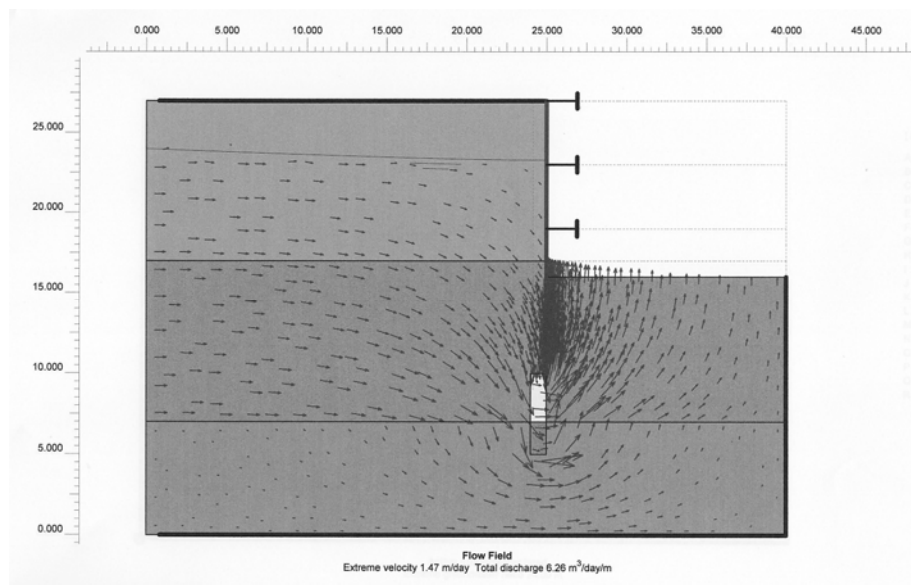
Combined with the previous analysis, the setting with grout curtain permeability 1×10^{-6} m/s and 5m-grout curtain length is the optimal ones. Using the same model but with the optimal settings, an analysis is carried out and the outcomes are as shown in the following figures.



Deformed Mesh



Flow Field Diagram



Active Water Head

The water drawdown is 1.0m and the total discharge per metre wall is 6.26m³ /day.

6.2 Ground Strengthening

Recall the example used in the previous section to demonstrate how the grout curtain works to achieve the water draw down requirement. The same cofferdam system is used, but in a different location of the same project.

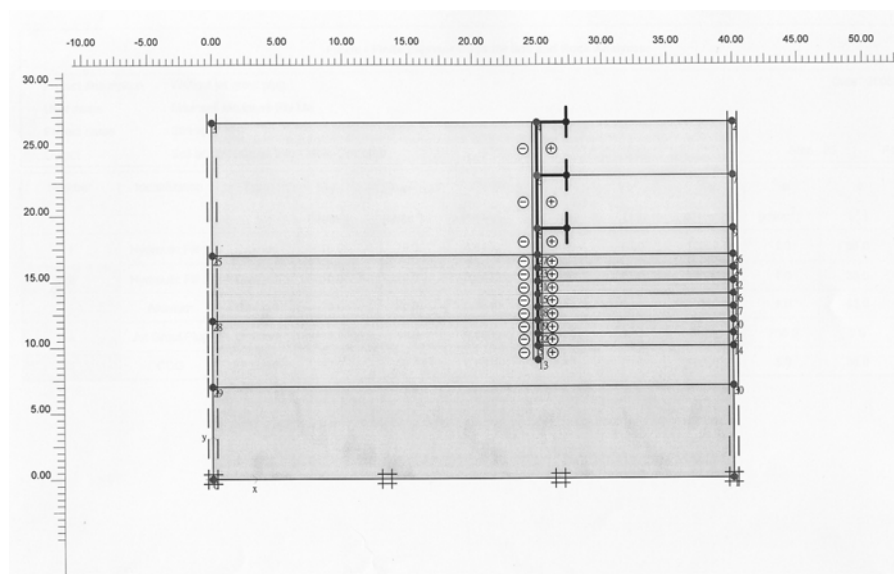
The site is right next to an existing Mass Transit Railway Tunnel. And there is a stringent requirement on the settlement induced by the excavation. It has to be less than 10mm.

The soil strata are similar to the previous example but different in thickness as well as one more CDG (Completely Decomposed Granite) layer. The properties of the CDG layer are detailed in the following table.

Name	Type	γ_{unsat} [kN/m ³]	γ_{sat} [kN/m ³]	k_x [m/day]	k_y [m/day]	ν [-]	E_{ref} [kN/m ²]	c_{ref} [kN/m ²]	ϕ [°]	Ψ [°]
CDG	Drained	17.0	19.0	0.864	0.864	0.30	60000.0	5.0	38	0.0

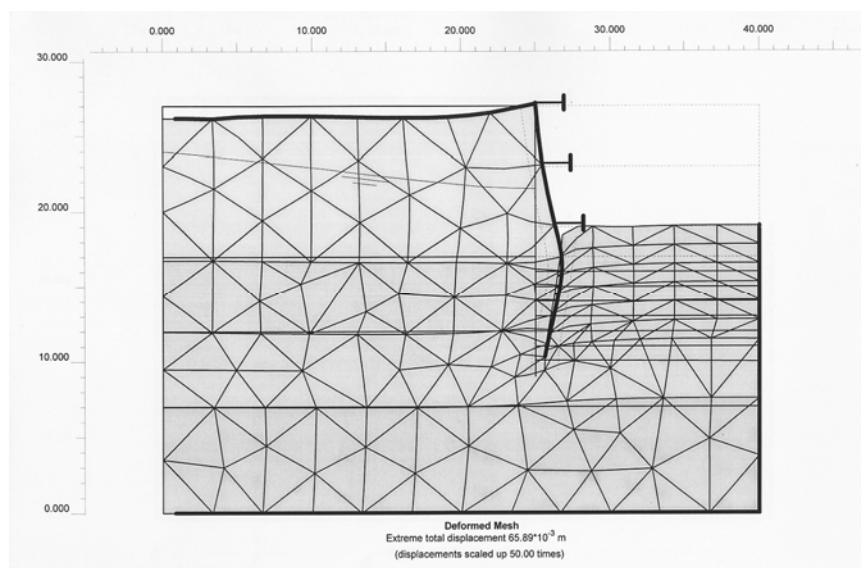
Table 9: Property of CDG

A model is set up as shown in the following figure to analyze the results if there is no any other grouting work done.

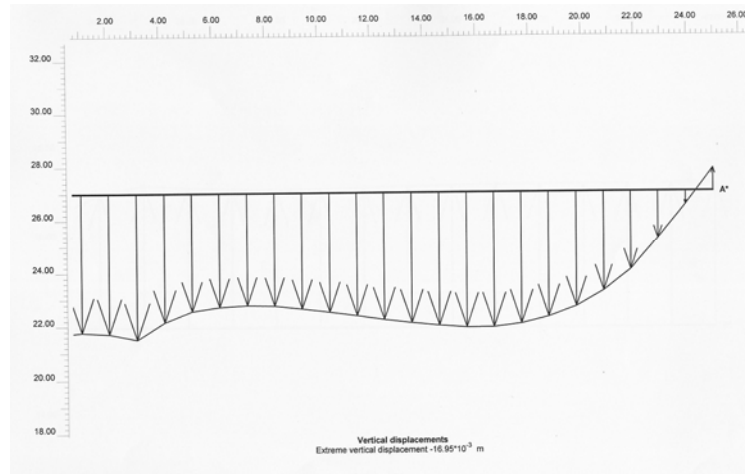


Geometry Model for the Case without Jet Grout Plug

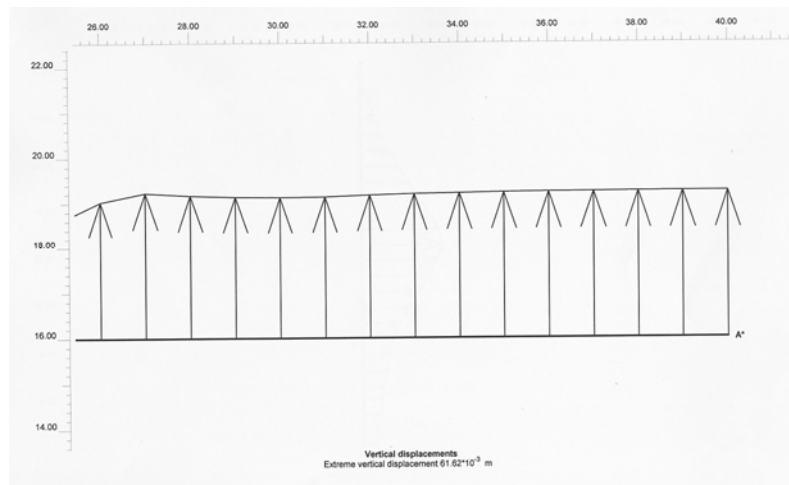
After the finite element analysis, the results are as shown in the following figures.



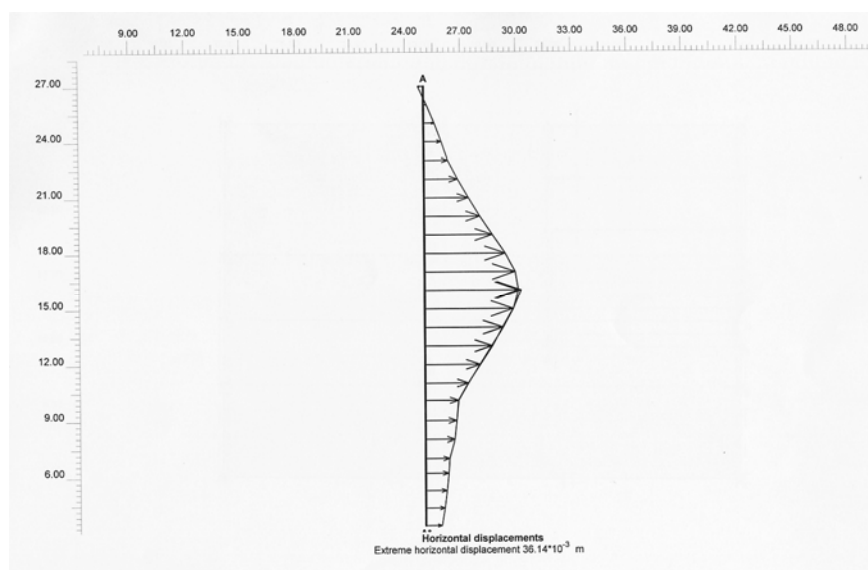
Deformed Mesh



Settlement outside the Excavation



Ground Heaving inside the Excavation



Deflection of the Cofferdam

One should note that the total displacement of the excavation is 65.98mm (16.95mm vertical settlement, 61.62mm heave and 36.14mm horizontal deflection of the wall). Actually, the settlement induced outside the excavation exceeds the required 10mm contract requirement and the deflection of the cofferdam is also not desirable with such magnitude.

One solution is to install a grout plug below the formation level to restrict the cofferdam deflection. With such strength requirement, the best grouting technique to do so is the jet grouting technique.

In order to ensure that the installed grout plug to possess the same property, it is cautious to perform a trial grouting test to determine the most appropriate jet grouting parameters for the main jet grouting work.

Name	Type	γ_{unsat} [kN/m ³]	γ_{sat} [kN/m ³]	k_x [m/day]	k_y [m/day]	ν [-]	E_{ref} [kN/m ²]	c_{ref} [kN/m ²]	φ [°]	Ψ [°]
Grout Plug	Drained	17.0	19.0	0.5	0.5	0.30	1.2E5	750.0	0.0	0.0

Table 10: Jet Grout Plug Property

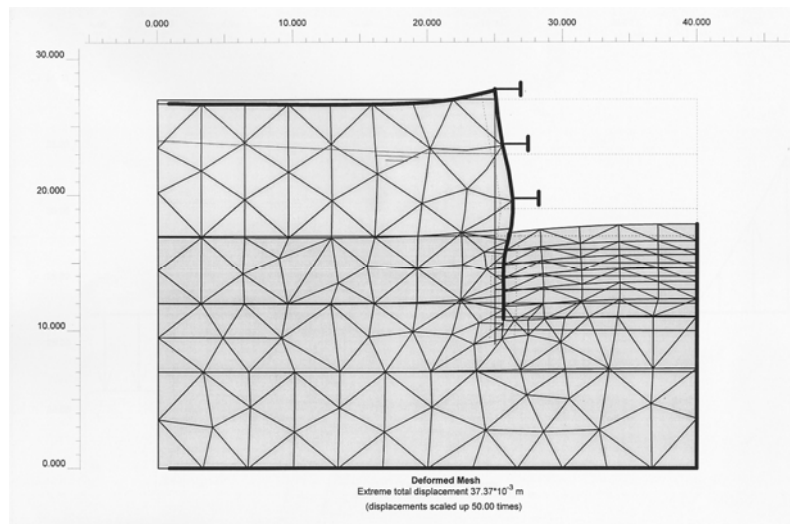
2D finite element analysis is used to check the extent of the jet grout plug required. The initial conditions and phases of calculation are exactly the same as that adopted for the grout curtain analysis.

In order to find the most optimal settings for the jet grout plug, the analysis starts with a 1m thick jet grout plug located 1m below the final formation level. The reason for this 1m depth is to allow for the preparation works required before the construction of the permanent work.

The result of the analysis is as expected. The extreme total displacement of the excavation is 50.93mm. Refer the following deformed mesh finite element model for details.

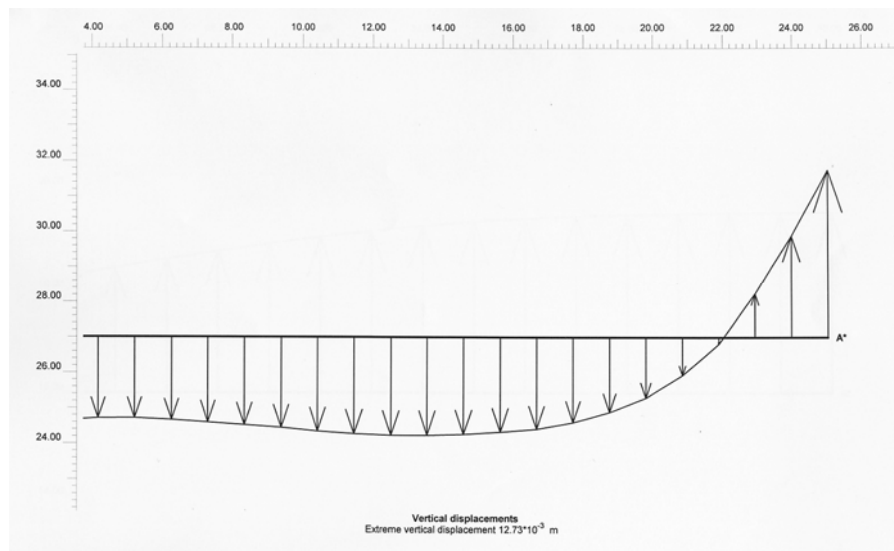
The horizontal displacement contour lines show that the maximum deflection of the cofferdam is 23.90mm. And the vertical displacement contour lines show that the maximum settlement outside the excavation is only 9.50mm. It is just smaller than the allowable value 10mm.

Hence, the advantage of using the jet grouting technique to improve the ground strength is obvious when compared with the TAM grouting technique. When using the TAM grouting technique to increase the soil strength, very high content of sodium silicate should be used per meter cube of chemical grout, as high as over 60%.

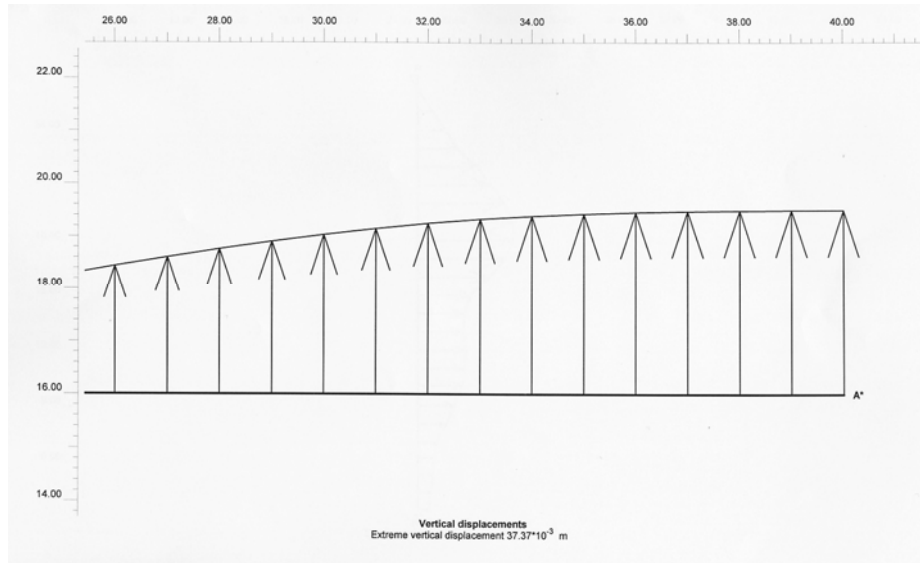


Deformed Mesh Model after Analysis

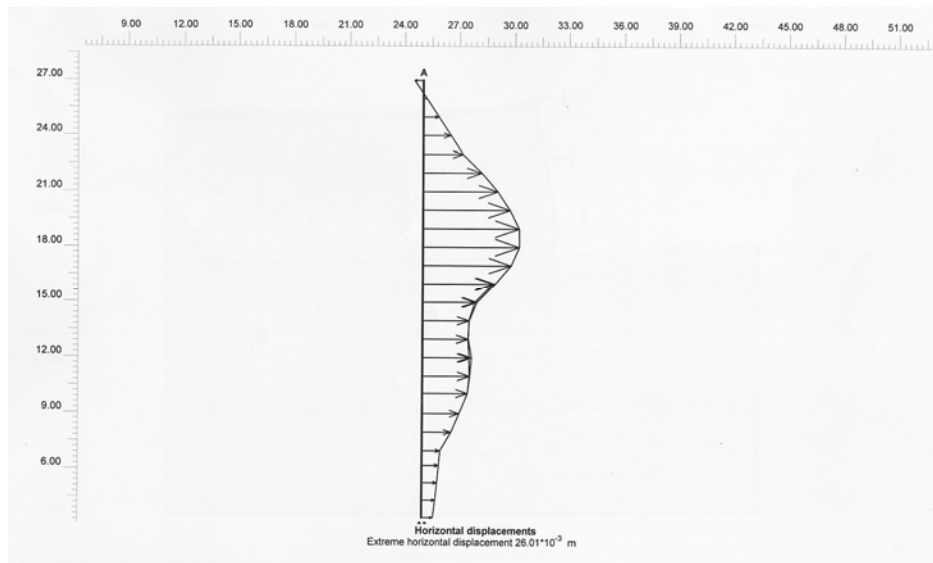
With such a high dosage of silicate, it is also required to use high concentration and extra purified organic reagent for the neutralization process to complete satisfactory. However, high content of sodium silicate and special made organic reagent implies higher cost per meter cube of grout. And the overall grouting operation has to be controlled carefully to avoid contamination to the surrounding ground water table because of the partial neutralization of all the reactants.



Horizontal Displacement Contours



Vertical Displacement Contours



Horizontal Displacement Contours

The analysis is continued with the unit thick jet grout plug located at 2m to 5m below the final formation level. The results are listed in the following table.

From the below table, it can be seen that the optimal depth of the jet grout plug is at 1m to 2m below the final formation level i.e. the location of the plug should be as near as possible the final excavation level.

Depth of Unit Jet Grout Plug	Outside Settlement	Inside Heaving	Deflection of Cofferdam	Total Displacement
Without Plug	16.95mm	61.62mm	36.14mm	65.89mm
1m	9.50mm	50.57mm	23.90mm	50.93mm
2m	7.83mm	48.36mm	25.51mm	48.36mm
3m	10.69mm	49.20mm	33.45mm	49.20mm
4m	9.2mm	46.32mm	28.00mm	46.32mm
5m	14.79mm	49.96mm	35.66mm	55.63mm

Table 11: Effects of Jet Grout Plug Depth

Thickness Jet Grout Plug	Outside Settlement	Inside Heaving	Deflection of Cofferdam	Total Displacement
Without Plug	16.95mm	61.62mm	36.14mm	65.89mm
1m	9.50mm	50.57mm	23.90mm	50.93mm
2m	8.83mm	45.12mm	23.50mm	45.12mm
3m	7.43mm	37.37mm	26.01mm	37.37mm
4m	7.51mm	30.03mm	27.30mm	30.72mm
5m	7.93mm	23.42mm	28.38mm	30.81mm

Table 12: Effect of Jet Grout Plug Thickness to Control Excavation Settlement

Then the analysis is repeated but in terms of jet grout plug with different thickness. Refer the above table for details.

From the above table, the 3m thick grout plug has the minimum settlement outside the excavation work. Therefore, 3m thick jet grout plug located at 1m below the final excavation level is the optimal settings for this model.

6.3 Control of Ground Settlement

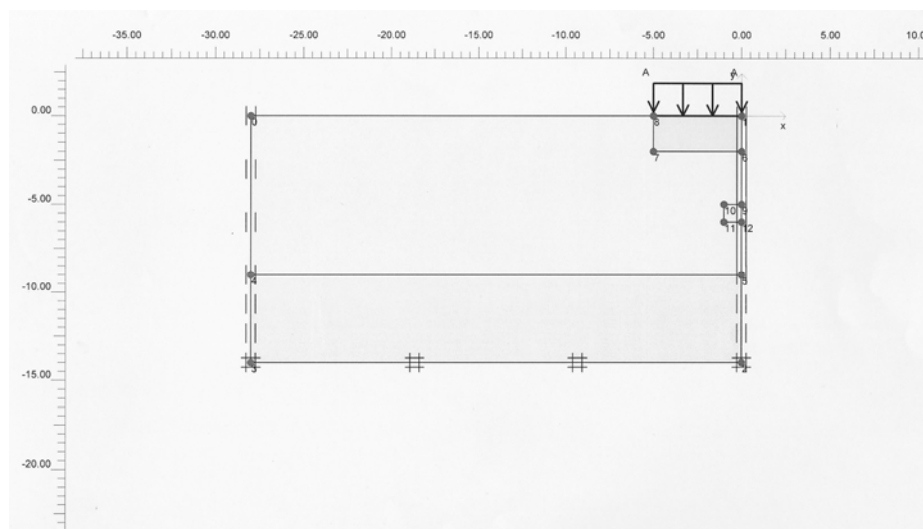
There are two grouting techniques that can control the ground settlement problem, namely the Compaction Grouting technique and the Compensation Grouting technique. Model simulation will be performed for these two techniques in the following sections.

The parameters for the modeling and analysis will be the same as far as possible. The aim is to have an apple-to-apple comparison at the end of analysis for both techniques so as to conclude which technique is the best for control of ground settlement.

6.3.1 Compaction Grouting

A raft foundation 10m long and 2m thick was carrying a load of 20kPa per meter settles because of a nearby trenching work. As the building accommodates sewage pumping facilities and the connection pipes are prone to damage caused by excessive differential settlement, it is required to stabilize and to compensate the settlement so as to prevent any excessive differential settlement from happening.

It is intended to use the compaction grouting method to achieve the soil stabilization and settlement compensation. As the compaction grouting method is a one-shot method, a finite element analysis is performed to predict the effect of the compaction grouting work. The aim is to optimize the compaction grouting design and to get the maximum benefits from the compaction grouting work. A geometry model is set up as per the following diagram. As the raft is symmetric, only half of the raft is presented in the model for analysis.



Geometry Model for Analysis

The topsoil layer is Fill, 9m thick and the bottom layer is completely decomposed granite (CDG) of 5m thick. The material properties for the analysis are as listed in the following table.

Name	Type	γ_{unsat} [kN/m ³]	γ_{sat} [kN/m ³]	k_x [m/day]	k_y [m/day]	ν [-]	E_{ref} [kN/m ²]	c_{ref} [kN/m ²]	φ [°]	Ψ [°]
Fill	Drained	18.0	18.0	4.3215	4.3215	0.25	7000	0.0	30.0	0.0
CDG	Drained	17.0	19.0	0.864	0.864	0.30	60000	5.0	38.0	0.0

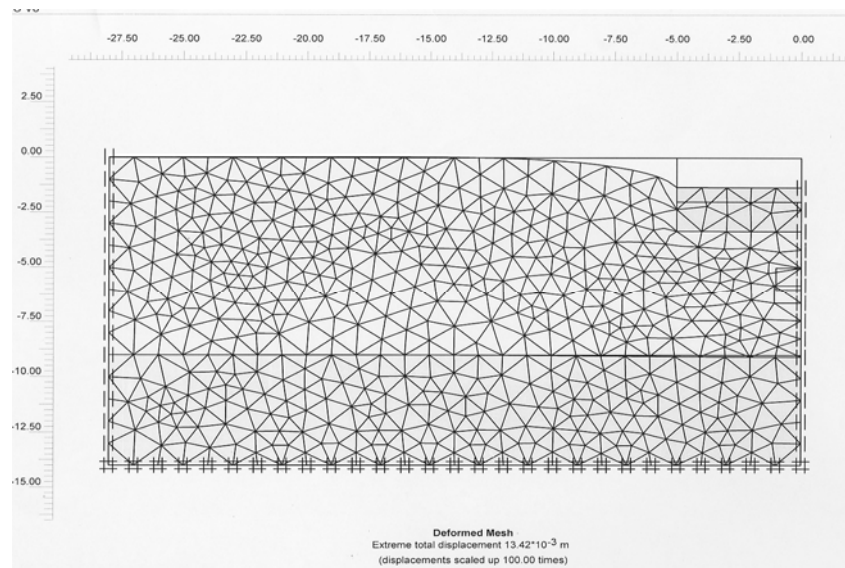
Table 13: Property of Soils for Analysis

Name	Type	γ_{unsat} [kN/m ³]	γ_{sat} [kN/m ³]	k_x [m/day]	k_y [m/day]	ν [-]	E_{ref} [kN/m ²]	c_{ref} [kN/m ²]	φ [°]	Ψ [°]
Raft	Drained	22.0	22.0	0.0086	0.0086	0.33	1.2E5	400.0	30.0	0.0

Table14: Property of Raft

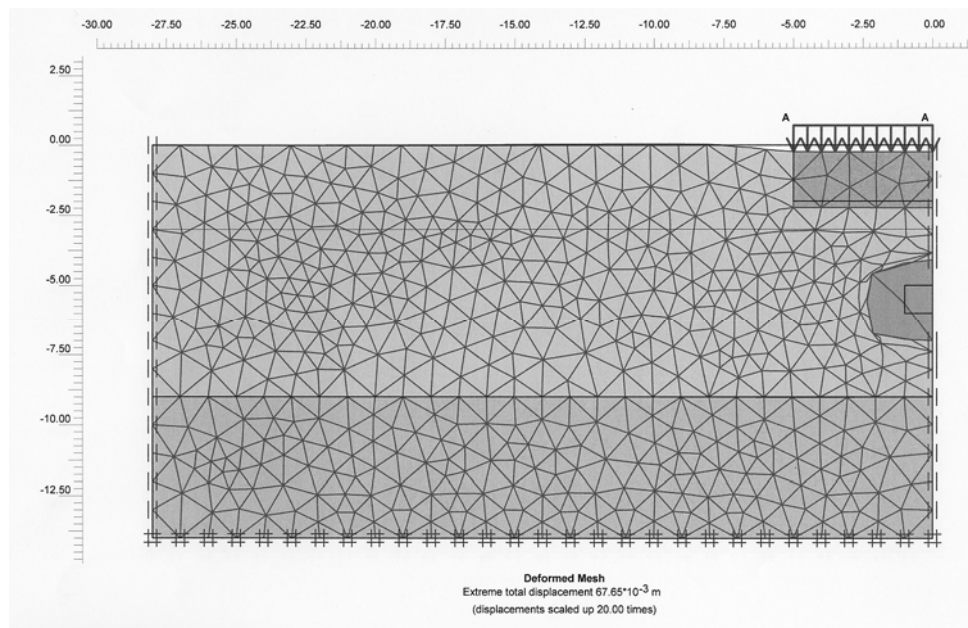
The grout bulb is injected 3m right below the center of the raft, and the volume of grout bulb will be 150 litres. To simulate this grout bulb volume after injection, a 1m x 1m x 1m grout cube is put at the future grout bulb location. With 15% volume strain increase, a grout bulb of 150 litre volume is created. The PLAXIS version 7.2 does not possess the function to impose an internal volumetric strain in soil cluster. The PLAXIS version 8 software is used.

Since the raft and the imposed load will induce a settlement, this settlement is calculated first and is taken as the base settlement reading. The following deformed mesh shows that the base settlement of the model is 13.42mm.



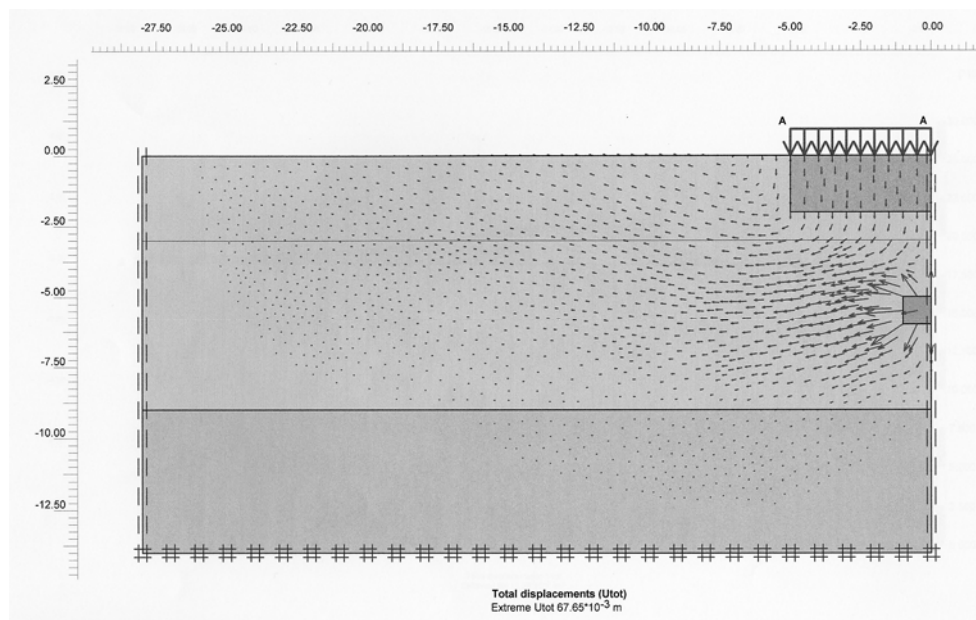
Deformed Mesh for the Base Settlement Reading

Then the grout cube is increased by 15% in volume by means of the Volumetric Strain Button of the software. After the analysis, it is shown that the total displacement is 67.65mm, something not expected.



Deformed Mesh after Compaction Grouting

From the deformed mesh, it is difficult to identify where this displacement coming from other than a slight heave of ground found about 3m away from the raft. The stress arrows diagram is then switched on to analyze the result.

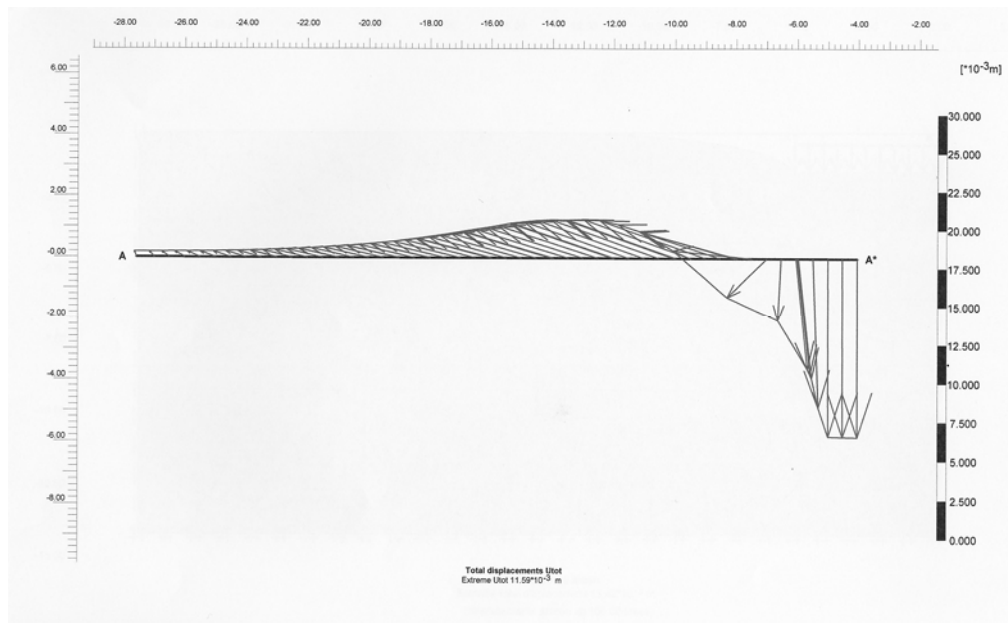


Stress Arrows Diagram

The length of the arrows represents their relative magnitude. The longer the tail is, the larger the magnitude will be. When refer to the grout bulb, it can be seen that the

arrows are in all directions. However, the majority of arrows in soil are to the left. It implies that there exists a large horizontal displacement instead of vertical displacement, as one would have expected before the analysis.

In order to have a closer look at the ground surface, a section A-A* is cut and the vertical displacement is shown as follows.



Section Diagram

It is found that the settlement of the raft is 11.51mm now and there is a heaving starting 3m from the rim of the raft. The maximum heaving happened at around 8m from the rim of the raft and is about 2.5mm in height. The improvement of the settlement is only 1.91mm.

It seems that the grout bulb has caused movement of the adjacent soil. Because of the loading from the raft and the rather loose nature of the fill material, the soil movement is confined mainly in the plane with the minor principal stress until it reaches a point where the influence of the raft loading is less.

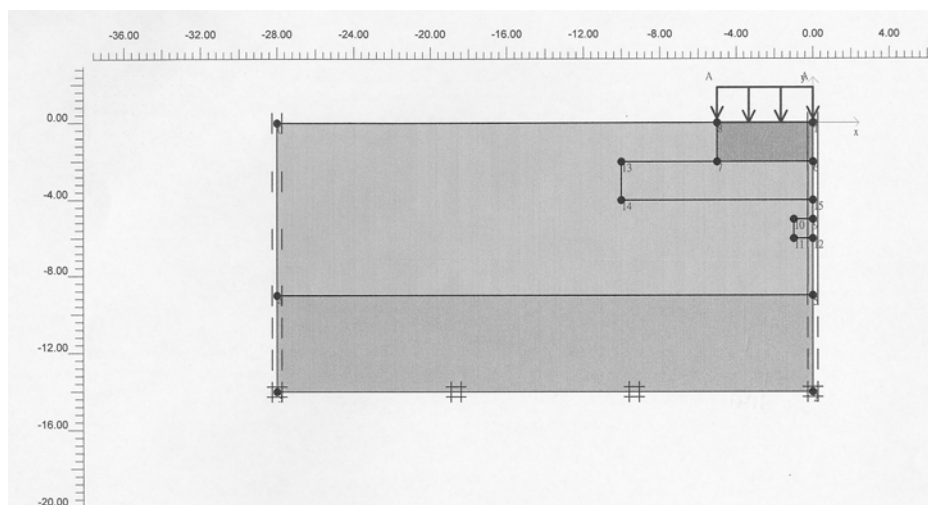
Different loadings are used for the same model to investigate the effects of loading to the result of the compaction grouting method. The table below lists out the details of the findings.

Imposed Load	Raft Base Settlement	Settlement after Grouting	Ground Heaving	Total Displacement	Settlement Improvement
15 kPa	10.04mm	7.91mm	3.02mm	67.70mm	2.13mm
20 kPa	13.42mm	11.51mm	2.50mm	67.65mm	1.91mm
25 kPa	16.91mm	15.49mm	2.26mm	69.07mm	1.42mm
30 kPa	20.48mm	19.34mm	2.17mm	70.29mm	1.14mm

Table 15: Effects of Loading on Compaction Grouting

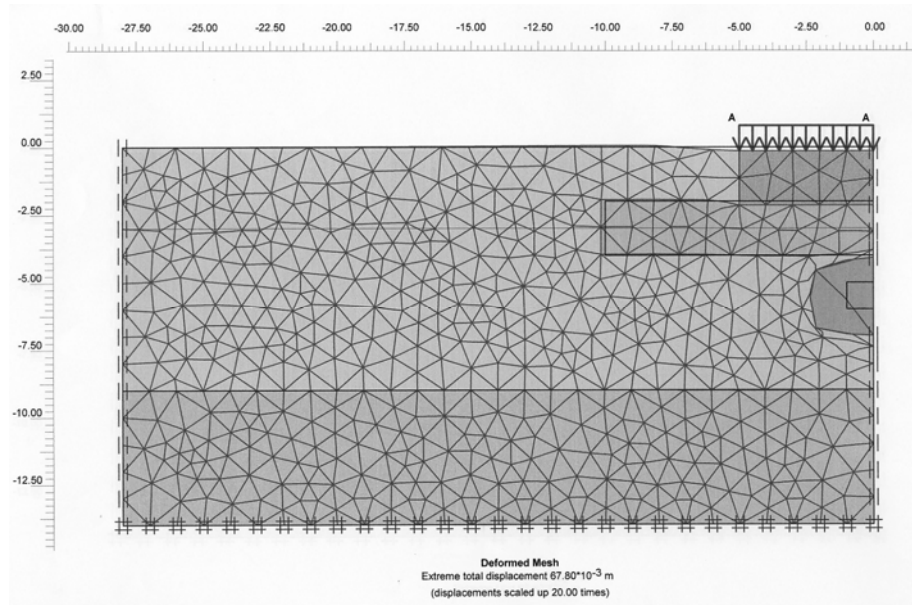
It is obvious that the settlement improvement diminishes as the imposed loading increases in magnitude. However, the total displacement increases as the load increases. It implies that the soil movement is larger as the load is larger, but the movement is mainly horizontal. The heavier loading forces the soil to expand sideward instead of a vertical direction.

That is why this method has to compact the upper portion of the ground first so that it becomes a dense cap to help contain the expanding grout at the lower levels. Refer the last paragraph of the Section 5.4.3 for more details. In this regard, a model is set up with a cap to simulate this idea to check the effects of cap on compaction grouting. Refer the following geometric model for details.

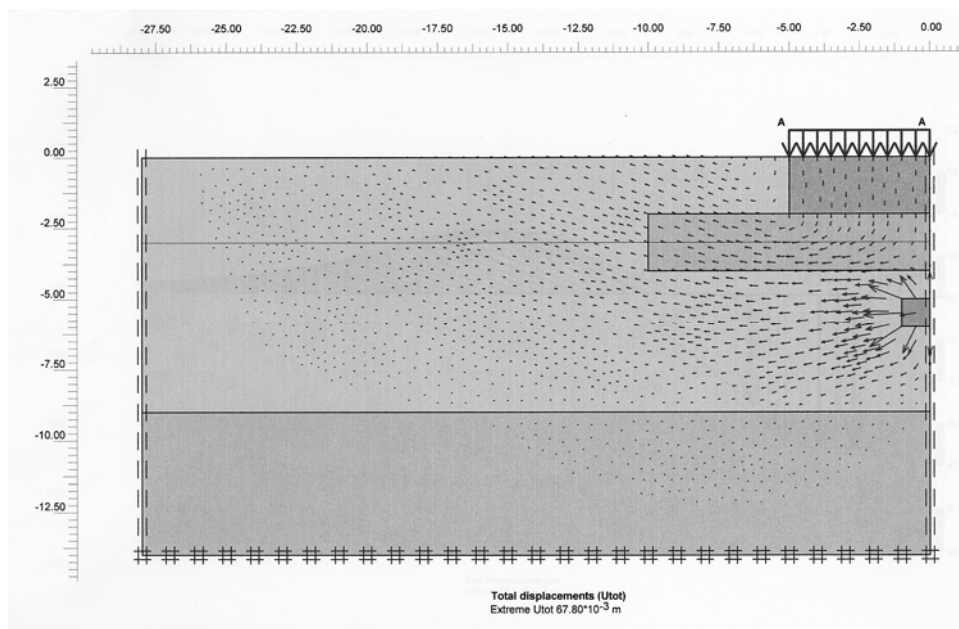


Geometric Model for Compaction Grouting with a Cap

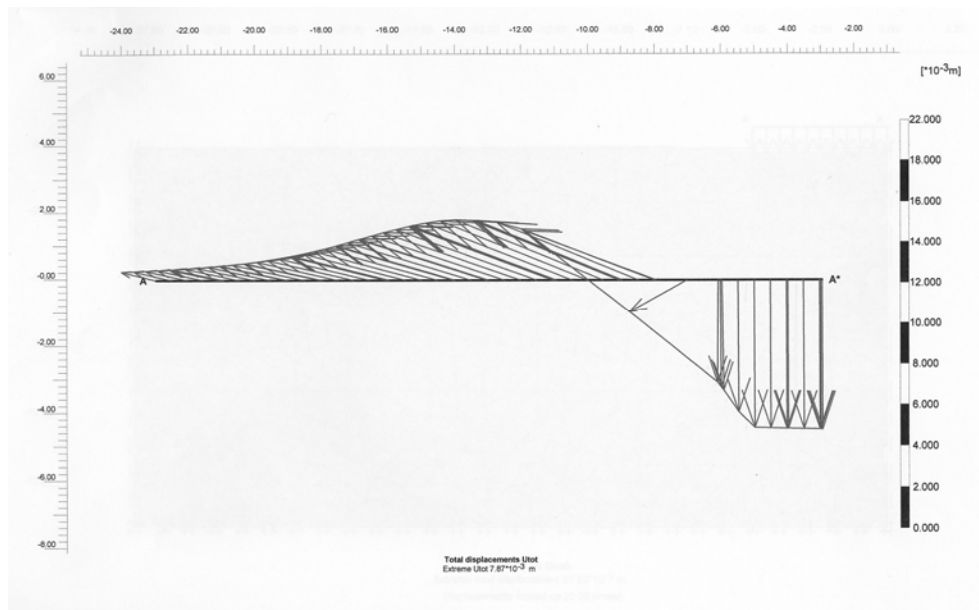
The cap is assumed to extend 5m from the rim of the raft with 2m thick. The strength of the cap is assumed to be 25% higher than the strength of the original Fill. It is also assumed that this cap is installed before the compaction grouting in the finite element calculation. Refer the following figures for the result of the analysis with 15 kPa imposed load.



Deformed Mesh for Compaction Grouting with Cap



Total Displacement Diagram



Cross Section at Ground Surface

The settlement improvement is 2.77mm, 0.64mm more than that without cap. Apparently, a 30% increase in settlement improvement. It also confirms that the compaction grouting method has to compact the upper portion of the ground first so that it becomes a dense cap to help contain the expanding grout at the lower levels. Refer the last paragraph of the Section 5.4.3 for more details.

Cap Strength (x Fill strength)	Raft Base Settlement	Settlement after Grouting	Ground Heaving	Total Displacement	Settlement Improvement
Without Cap	10.04mm	7.91mm	3.02mm	67.70mm	2.13mm
1.25 times	10.04mm	7.27mm	3.09mm	67.80mm	2.77mm
1.50 times	10.04mm	7.17mm	3.09mm	67.70mm	2.87mm
2.00 times	10.04mm	6.94mm	3.12mm	68.12mm	3.10mm
3.00 times	10.04mm	6.87mm	3.33mm	68.95mm	3.17mm

Table 16: Effects of Cap Strength on Compaction Grouting with 15 kPa Load

In order to evaluate the effects of the cap strength on compaction grouting as well, a series of analysis is also performed. The results are listed in the above table.

It seems that the settlement improvement is not directly proportional to the cap strength. Provided the cap strength is slightly higher than the Fill strength, the settlement improvement is increased substantially. It is not worthwhile to increase the cap strength much higher than the Fill strength.

The same model is used to analyze the effects of loading on compaction grouting with cap. To have a consistent analysis, the cap strength is set to be 1.25 x Fill strength for all loadings. The following table details the results of the analysis.

Imposed Load	Raft Base Settlement	Settlement after Grouting	Ground Heaving	Total Displacement	Settlement Improvement
15 kPa	10.04mm	7.27mm	3.09mm	67.80mm	2.77mm
20 kPa	13.42mm	11.05mm	2.75mm	68.44mm	2.37mm
25 kPa	16.91mm	14.83mm	2.41mm	69.49mm	2.08mm
30 kPa	20.48mm	18.78mm	2.33mm	71.21mm	1.70mm

Table 17: Effects of Loading on Compaction Grouting with Cap

It is also of interesting to check if or not the same improvement percentage is obtained for different loadings for compaction grouting with and without cap. Refer the table in the following for details.

Imposed Load	Settlement Improvement (Without Cap)	Settlement Improvement (With Cap)	Increasing Percentage
15 kPa	2.13mm	2.77mm	30.05%
20 kPa	1.91mm	2.37mm	24.08%
25 kPa	1.42mm	2.08mm	46.48%
30 kPa	1.14mm	1.70mm	49.12%

Table 18: Comparison of Settlement Improvement

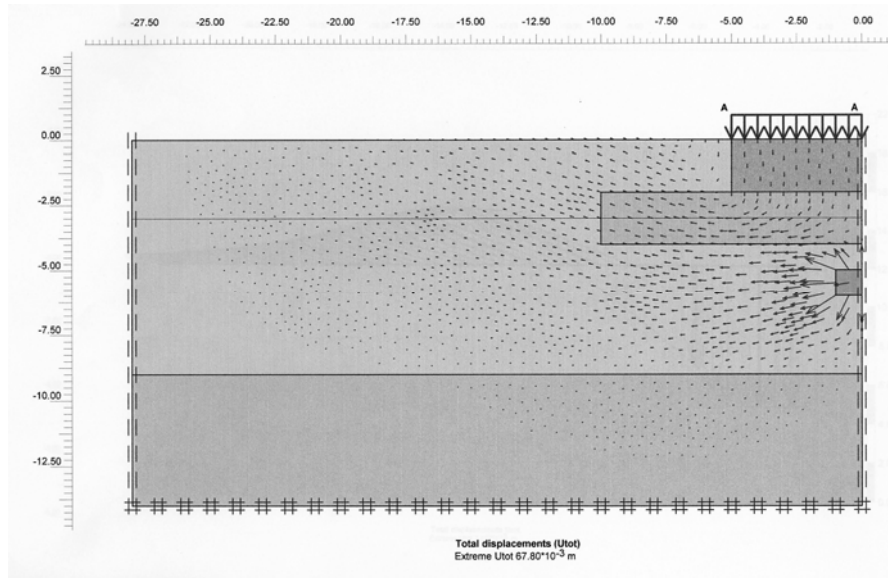
It is obvious that the improvement is more enhance for greater loading.

It is also of interest to study the effects of grouting depth on the compaction grouting method. The cap strength is set to be 1.25 x Fill strength and the imposed load is kept constant at 15 kPa so as to have comparable results.

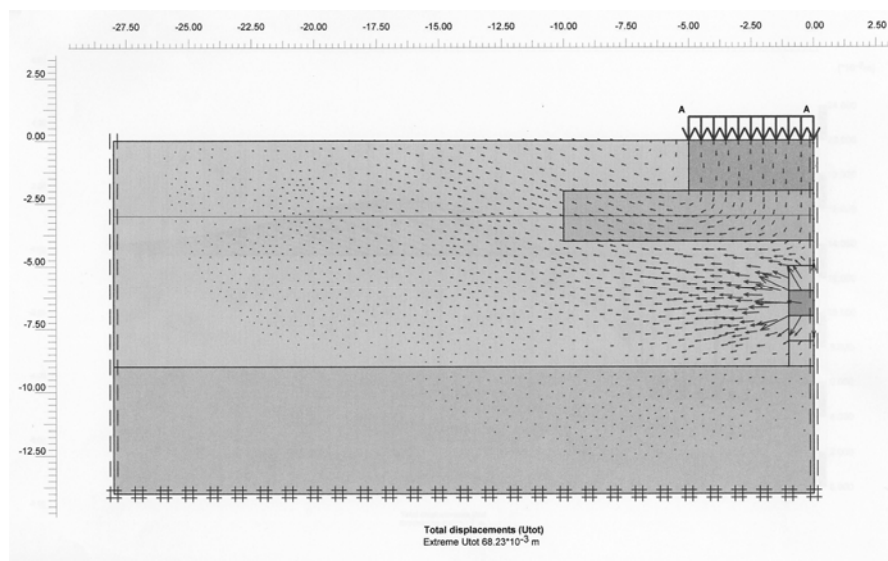
Grouting Depth	Raft Base Settlement	Settlement after Grouting	Ground Heaving	Total Displacement	Settlement Improvement
5m	10.04mm	7.27mm	3.09mm	67.80mm	2.77mm
6m	10.04mm	8.41mm	3.24mm	68.23mm	1.63mm
7m	10.04mm	7.96mm	3.21mm	69.55mm	2.08mm
8m	10.04mm	6.44mm	3.33mm	81.96mm	3.60mm

Table 19: Effects of Grouting Depth on Compaction Grouting with Cap

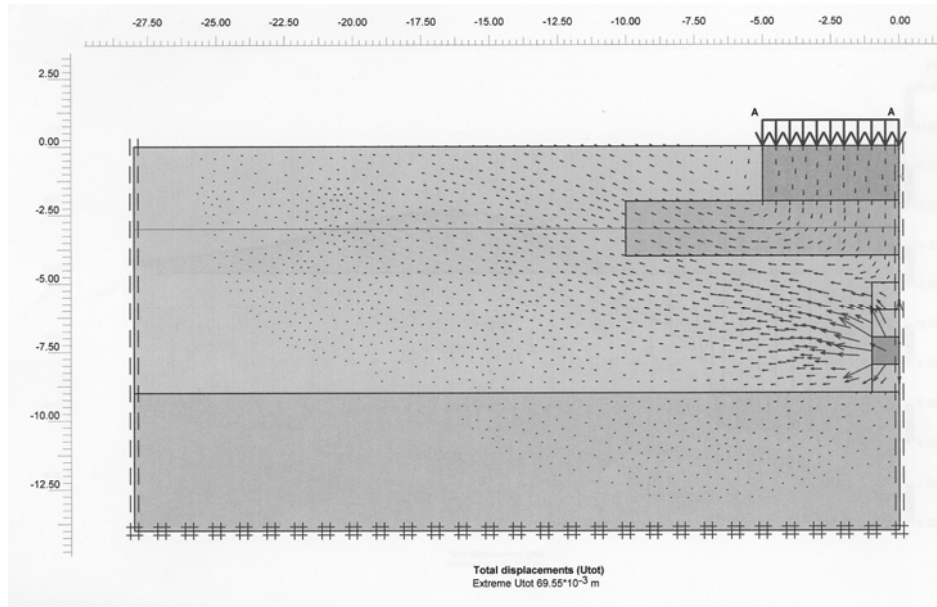
At first glance, there seems no correlation between grouting depth and settlement improvement. However, if one looks into detail the Stress Arrow Diagrams, there are reasons for the results got from the analysis.



Most of the soil movement to the right, but some inclined upwards, especially at the top of the grout cube.

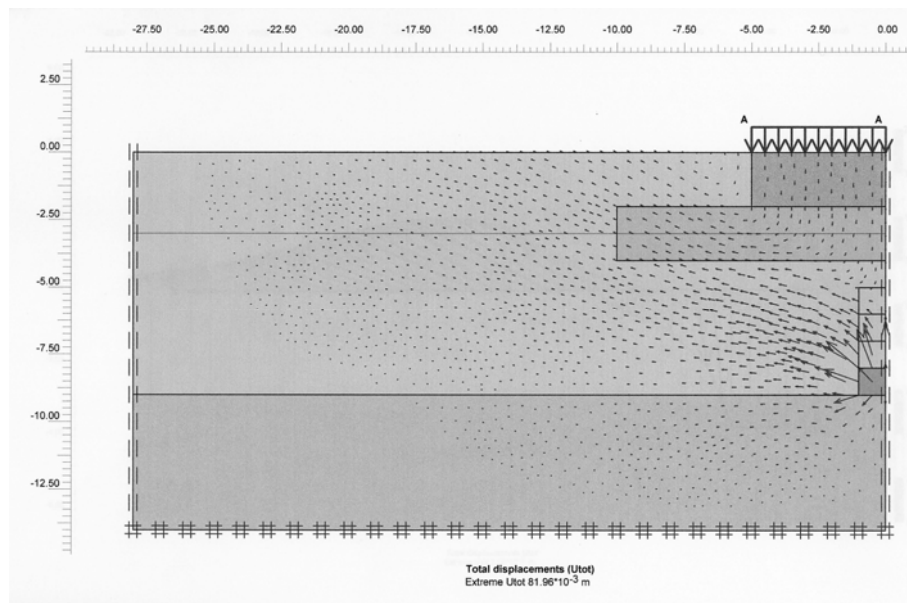


Nearly all the soil movements are to the left. And it is why the settlement improvement is the least.



Stress Arrow Diagram with 7m Grouting Depth

The expanding grout bulb causes soil movement in both upward and downward directions. However, the firm CDG layer rebound the movement upwards and cause the soil movement from predominately sideward to incline upward. Thus more settlement improvement is obtained.



Stress Arrow Diagram with 8m Grouting Depth

The firm CDG layer rebound the expanding Fill upward at a steeper angle. Hence, it causes the best settlement improvement. This finding is important for determining the grout pipe location if compaction grouting is used to lift settled structures. It is important to put the grout pipes as near as possible an underlying firm soil layer.

Finally, the same model is used to study the effects of Fill permeability on compaction grouting. Again, the imposed loading is confined to 15 kPa and cap

strength is 1.25 times Fill strength in order to be consistent in the analysis. The results are presented in the table below.

Fill Permeability	Total Displacement (Deformed Mesh)	Total Displacement (Cross Section at G.L.)
1.0 x	67.80mm	7.87mm
0.5 x	67.67mm	7.86mm
0.1 x	67.67mm	7.86mm
0.01 x	67.80mm	7.87mm

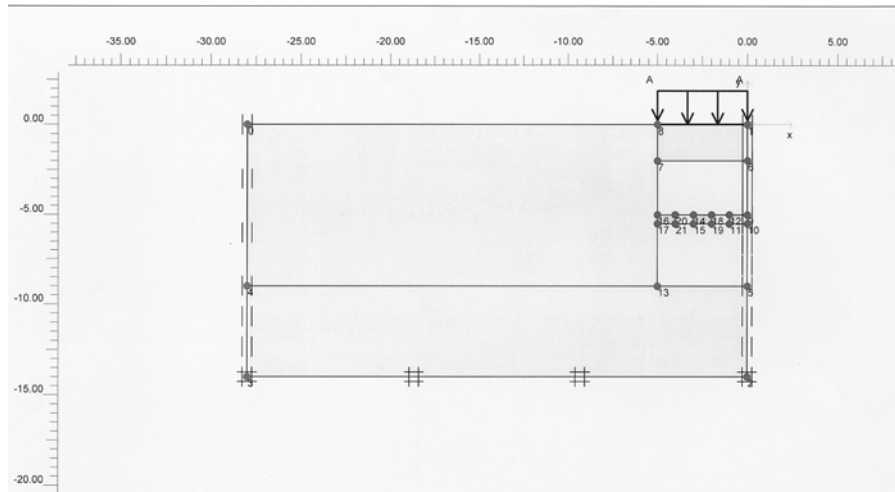
Table 20: Effects of Fill Permeability on Compaction Grouting

Even though the permeability of the Fill is changed, there is no change in any displacement values. Hence, permeability has nothing to do with settlement improvement.

6.3.2 Compensation Grouting

Recall the same problem as described in the Compaction Grouting section. Instead of using the compaction grouting technique, the compensation grouting technique is deployed to achieve the soil stabilization and settlement compensation.

A finite element analysis is also performed to predict the effect of the compensation grouting work to optimize the grouting design and precautions to take. A geometry model is set up as per the following diagram. As the raft is symmetric, only half of the raft is presented in the model for analysis.



Geometry Model

The topsoil layer is Fill, 9m thick and the bottom layer is CDG of 5m thick. The material properties of the soils and the raft for the analysis are same as that used for the compaction grouting analysis. They are not repeated here.

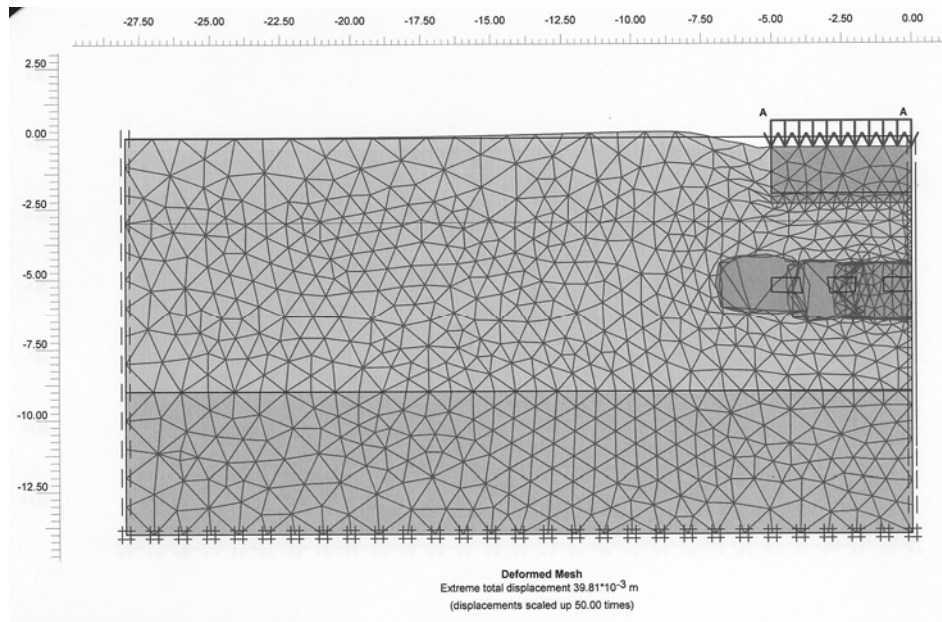
The grout fractures are injected 3m right below the center of the raft, and the total volume of grout fractures will be 150 litres, same as that for compaction grouting solution so as to have an apple-to-apple comparison. To simulate this grout fracture volume after injection, three 0.5m x 1m x 1m grout blocks are put at the future grout fracture locations. With 10% volume strain increase, grout fractures of total 150 litre volume are created. Again, the PLAXIS version 8 software is used.

The reason to use the three small grout blocks to simulate the grout fractures is that it is the closest model to the type of TAM pipes used for this grouting technique. Normally, the TAM pipes for compensation grouting have rubber sleeves at 1m apart. And the sleeves are grouted at alternate positions. The reserved rubber sleeves are for future regrouting purpose.

However, this model does not really represent the grout fractures formed. The actual grout fractures formed are mainly of few mm thicknesses and are in layers following the minor principal stress plane. The only resemblance is that, if the grout is injected in stages with small quantity, the grout fractures should be confined in the treatment zone and look like the small grout blocks as described.

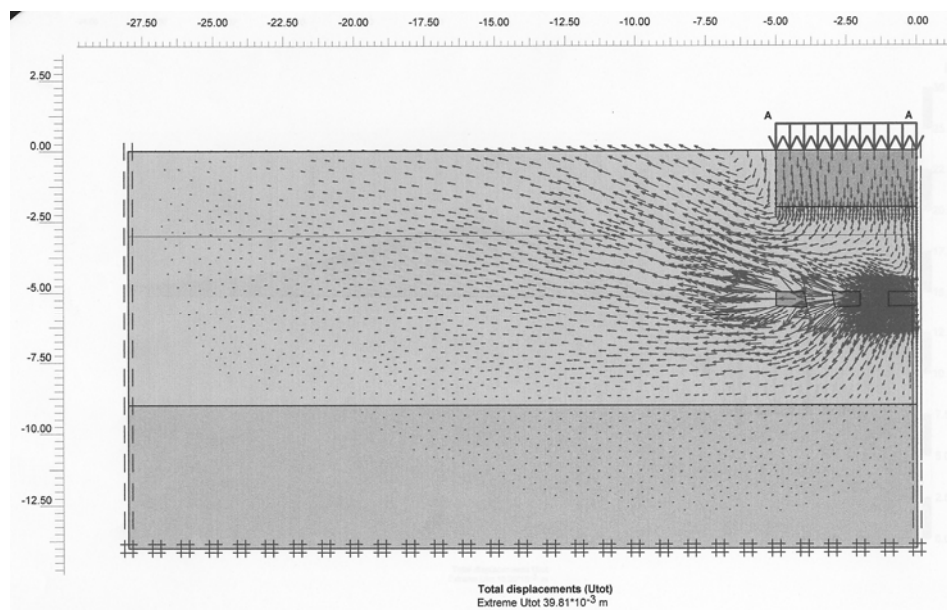
Since the raft and the imposed load will induce a settlement, this settlement is calculated first and is taken as the base settlement reading. The following deformed mesh shows that the base settlement of the model is 13.59mm.

Then the grout cube is increased by 10% in volume by means of the Volumetric Strain Button of the software. After the analysis, it is shown that the total displacement is 39.81mm. It is less than that for the compaction grouting but still something not expected.



Deformed Mesh after Compensation Grouting

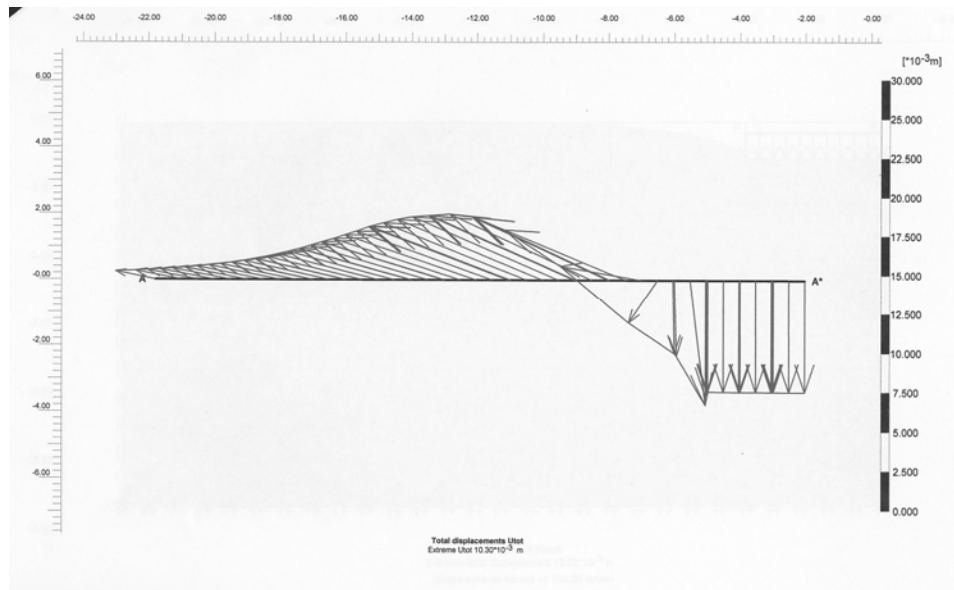
From the deformed mesh, it is difficult to identify where this displacement coming from other than a slight heave of ground found near the raft. The stress arrows diagram is then switched on to analyze the result.



Stress Arrows Diagram

The length of the arrows represents their relative magnitude. The longer the tail is, the larger the magnitude will be. It can be seen that the majority of arrows in soil are inclined to the left. It implies that there exist large horizontal and sub-vertical displacements instead of pure vertical displacement.

In order to have a closer look at the ground surface, a section is cut at ground level and the displacement is shown as follows.



Cross Section Diagram

It is found that the settlement of the raft is 7.03mm now. The ground starts to heave from the rim of the raft. The maximum heaving happened right next to the rim of the raft and is about 4.29mm in height. The improvement of the settlement is 6.56mm.

Hence, the compensation grouting technique is more efficient than the compaction grouting technique for settlement control. Apparently, the small grout blocks on the left hand side restrict the displacements caused by the two inner grout blocks. Thus make it cause more heaving.

It seems that the grout fracture has caused movement of the adjacent soil, same as the grout bulb for compaction grouting.

That is why this method has to compact and tighten the upper portion of the ground first so that it becomes a dense cap to help contain the expanding grout at the lower levels. This requirement is the same for the two grouting techniques applied for control of settlement or structure uplifting.

Different loadings are used for the same model to investigate the effects of loading to the result of the compensation grouting method. The table below lists out the details of the findings.

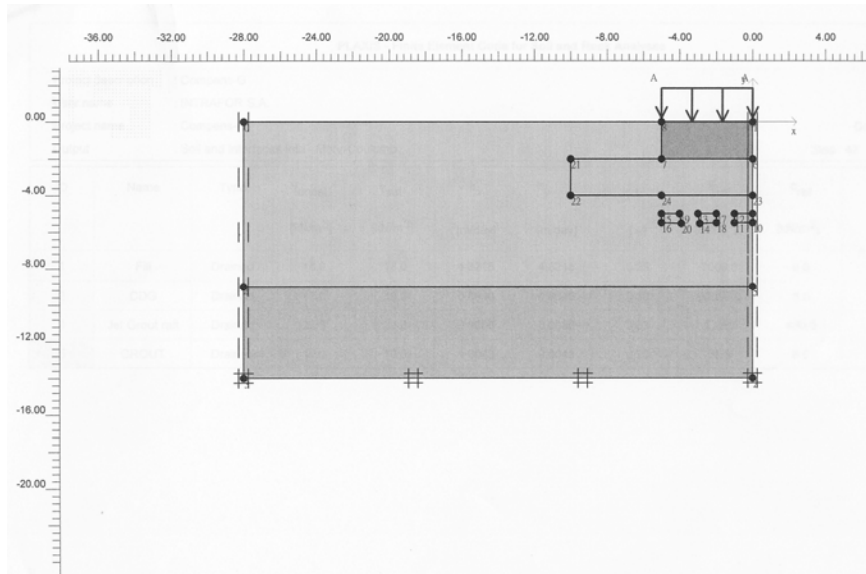
Imposed Load	Raft Base Settlement	Settlement after Grouting	Ground Heaving	Total Displacement	Settlement Improvement
15 kPa	10.27mm	1.74mm	4.72mm	38.46mm	8.53mm
20 kPa	13.59mm	7.03mm	4.29mm	39.81mm	6.56mm
25 kPa	17.09mm	11.93mm	3.73mm	41.39mm	5.16mm
30 kPa	20.71mm	16.60mm	3.81mm	43.04mm	4.11mm

Table 21: Effects of Loading on Compensation Grouting

It is obvious that the settlement improvement diminishes as the imposed loading increases in magnitude. However, the total displacement increases as the load increases. It implies that the soil movement is larger as the load is larger, but the movement is mainly horizontal. The heavier loading forces the soil to expand sideward instead of a vertical direction.

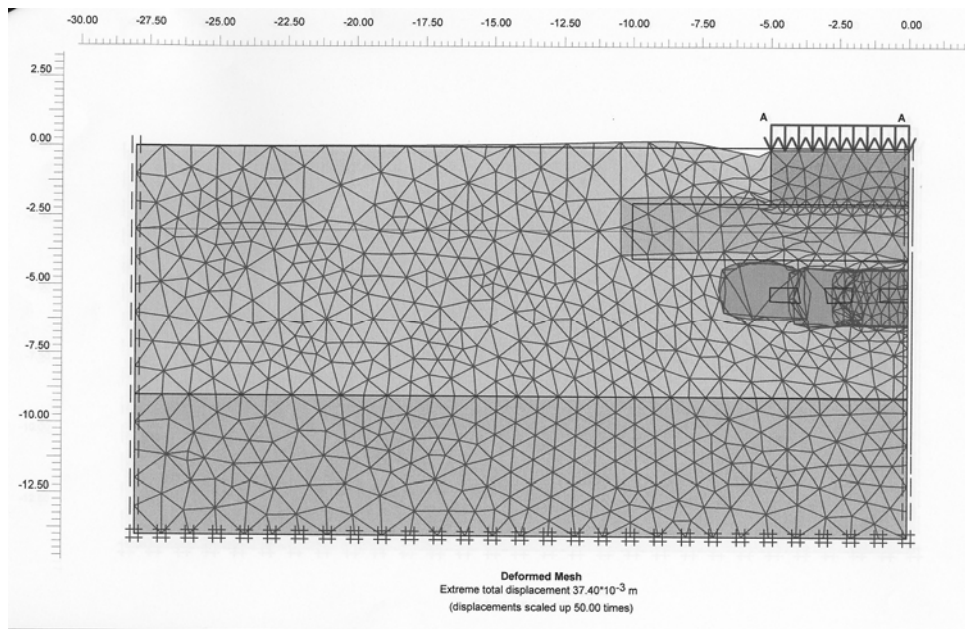
That is why this method has to consolidate the upper portion of the ground first so that it becomes a dense cap to help contain the expanding grout at the lower levels. Refer the last paragraph of the Section 5.5.3 for more details.

In this regard, a model is set up with a cap to simulate this idea to check the effects of cap on compensation grouting. Refer the following geometric model for details.

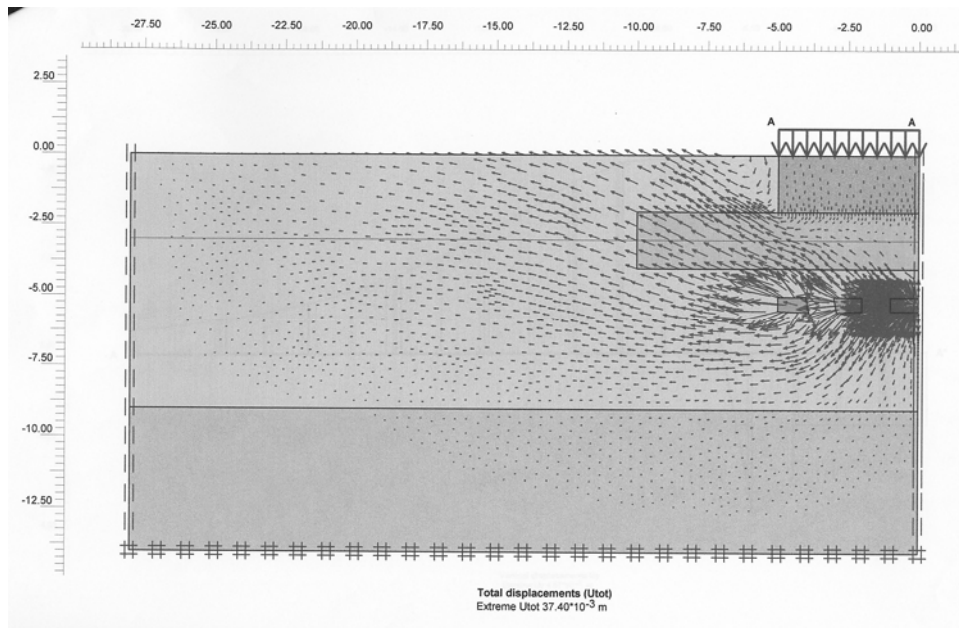


Geometric Model for Compensation Grouting with a Cap

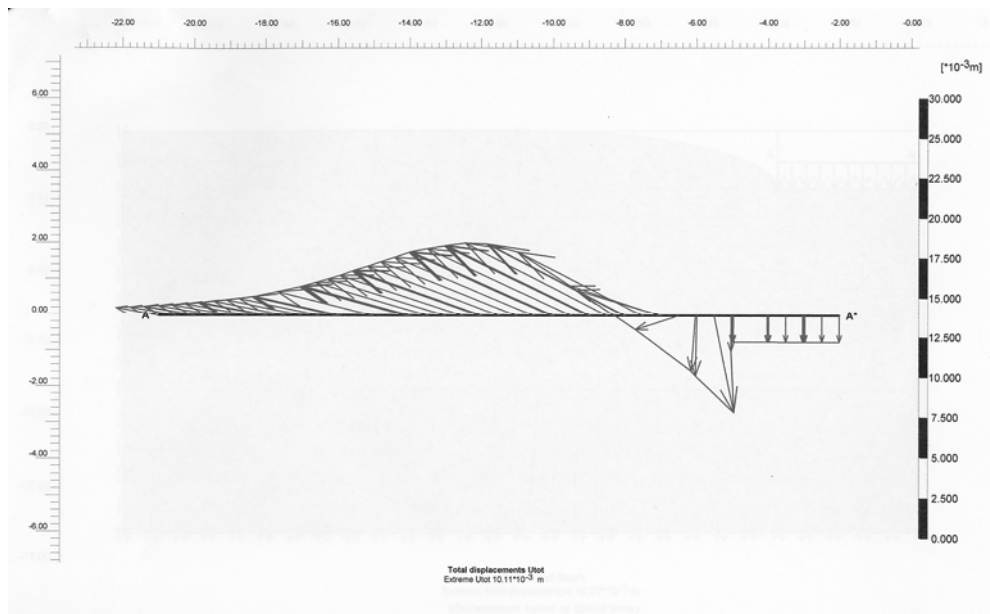
The cap is assumed to extend 5m from the rim of the raft with 2m thick. The strength of the cap is assumed to be 25% higher than the strength of the original Fill. It is also assumed that this cap is installed before the compensation grouting in the finite element calculation. Refer the following figures for the result of the analysis with 15 kPa imposed load.



Deformed Mesh for Compensation Grouting with Cap



Total Displacement Diagram



Cross Section at Ground Surface

The settlement improvement is 8.52mm, nearly the same as that without cap (8.53mm). In order to evaluate the effects of the cap strength on compensation grouting as well, a series of analysis is also performed. The results are listed in the following table.

Cap Strength (x Fill strength)	Raft Base Settlement	Settlement after Grouting	Ground Heaving	Total Displacement	Settlement Improvement
Without Cap	10.27mm	1.74mm	4.72mm	38.46mm	8.53mm
1.25 times	10.27mm	1.75mm	4.57mm	37.40mm	8.52mm
1.50 times	10.27mm	1.75mm	4.69mm	37.32mm	8.52mm
2.00 times	10.27mm	1.94mm	4.83mm	37.25mm	8.33mm

Table 22: Effects of Cap Strength on Compensation Grouting with 15 kPa Load

It seems that the settlement improvement is not enhanced by the cap strength. It is contrary to the effect of cap on compaction grouting.

Imposed Load	Raft Base Settlement	Settlement after Grouting	Ground Heaving	Total Displacement	Settlement Improvement
15 kPa	10.27mm	1.75mm	4.57mm	37.40mm	8.52mm
20 kPa	13.70mm	6.36mm	4.09mm	38.75mm	7.34mm
25 kPa	17.21mm	11.15mm	4.00mm	40.24mm	6.06mm
30 kPa	20.81mm	15.64mm	3.64mm	41.82mm	5.17mm

Table 23: Effects of Loading on Compensation Grouting with Cap

Anyway, the same model is used to analyze the effects of loading on compensation grouting with cap. To have a consistent analysis, the cap strength is set to be 1.25 x Fill strength for all loadings. The following table details the results of the analysis.

It is also of interesting to check if or not the same improvement percentage is obtained for different loadings for compensation grouting with and without cap. Refer the table in the following for details.

Imposed Load	Settlement Improvement (Without Cap)	Settlement Improvement (With Cap)	Increasing Percentage
15 kPa	8.53mm	8.52mm	0.00%
20 kPa	6.56mm	7.34mm	11.89%
25 kPa	5.16mm	6.06mm	17.44%
30 kPa	4.11mm	5.17mm	25.79%

Table 24: Comparison of Settlement Improvement

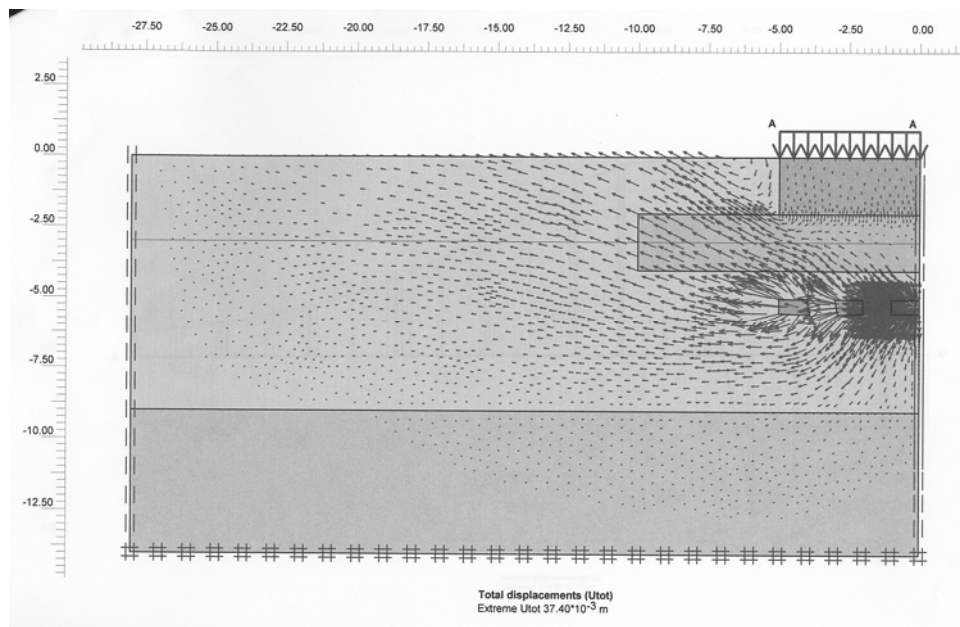
It is obvious that the improvement is more enhance for greater loading. But, when compared with the compaction grouting technique, the effect of the cap to settlement improvement is much less.

It is also of interest to study the effects of grouting depth on the compensation grouting technique. The cap strength is set to be 1.25 x Fill strength and the imposed load is kept constant at 15 kPa so as to have comparable results.

Grouting Depth	Raft Base Settlement	Settlement after Grouting	Ground Heaving	Total Displacement	Settlement Improvement
5m	10.27mm	1.75mm	4.57mm	37.40mm	8.52mm
6m	10.27mm	2.95mm	5.00mm	39.26mm	7.32mm
7m	10.27mm	3.91mm	5.22mm	38.17mm	6.36mm
8m	10.27mm	1.71mm	4.91mm	39.22mm	8.56mm

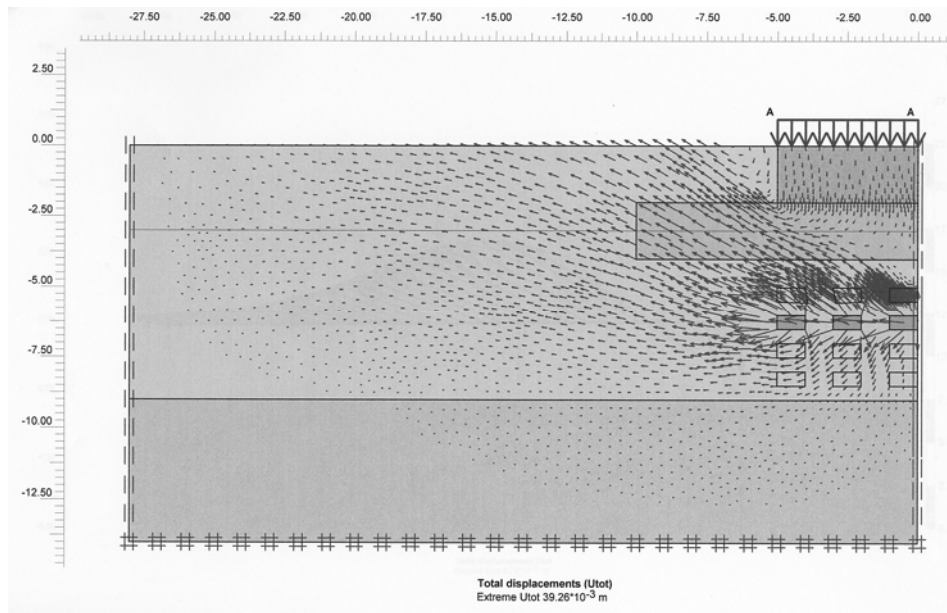
Table 25: Effects of Grouting Depth on Compensation Grouting with Cap

At first glance, there seems no correlation between grouting depth and settlement improvement. However, if one looks into detail the Stress Arrow Diagrams, there are reasons for the results got from the analysis.



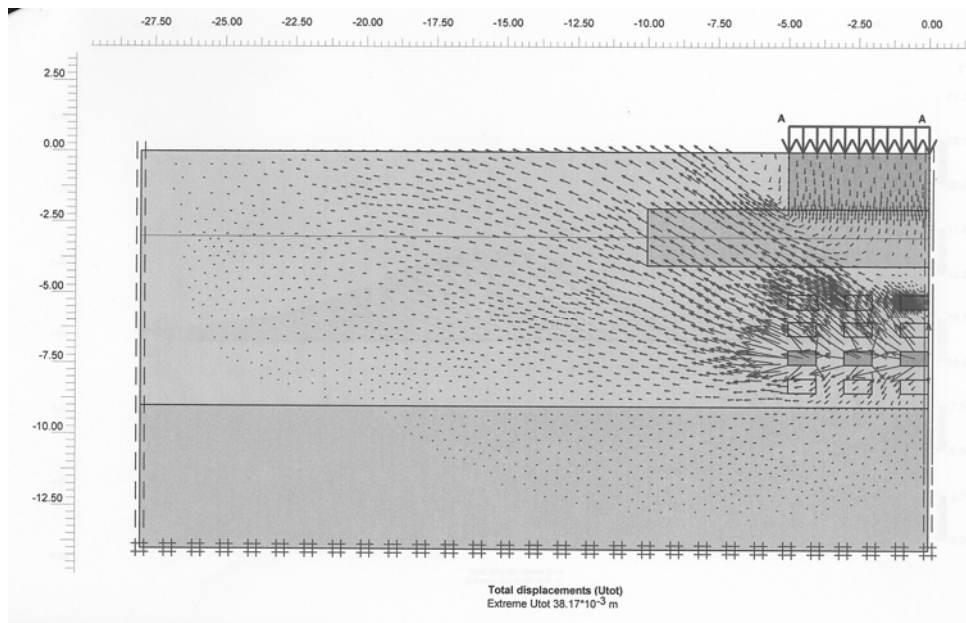
Stress Arrow Diagram with 5m Grouting Depth

Most of the soil movement to the right, but some inclined upwards.



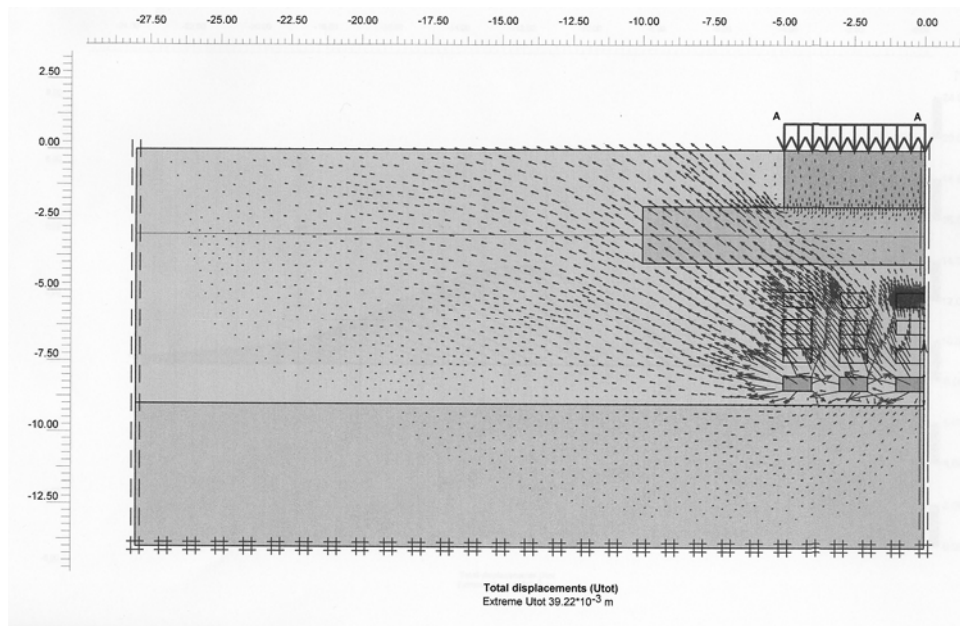
Stress Arrow Diagram with 6m Grouting Depth

There are more soil movements to the left. It is why the settlement improvement is the less than that at 5m.



Stress Arrow Diagram with 7m Grouting Depth

There are even more soil movements to the left. It is why the settlement improvement is the least.



Stress Arrow Diagram with 8m Grouting Depth

The firm CDG layer rebound the expanding Fill upward at a steeper angle. Hence, it causes the best settlement improvement. This finding is important for determining the grout pipe location if compensation grouting is used to lift settled structures. It is important to put the grout pipes as near as possible an underlying firm soil layer.

Finally, the same model is used to study the effects of Fill permeability on compensation grouting. Again, the imposed loading is confined to 15 kPa and cap strength is 1.25 times Fill strength in order to be consistent in the analysis. The results are presented in the table below.

Fill Permeability	Total Displacement (Deformed Mesh)	Total Displacement (Cross Section at G.L.)
1.0 x	38.15mm	10.32mm
0.5 x	38.15mm	10.32mm
0.1 x	38.15mm	10.32mm
0.01 x	38.15mm	10.32mm

Table 26: Effects of Fill Permeability on Compensation Grouting

Even though the permeability of the Fill is changed, there is no change in any displacement values. Hence, permeability has nothing to do with settlement improvement.

6.3.3 Comparison of Compaction Grouting and Compensation Grouting

To know which grouting technique has a better performance in the control of ground settlement, the results of all the above finite element analysis are presented in comparison tables as shown in the following.

Imposed Load	Compaction Grouting (without cap)	Compaction Grouting (with cap)	Compensation Grouting (without cap)	Compensation Grouting (with cap)	Difference
15 kPa	2.13mm	<u>2.77mm</u>	8.53mm	8.52mm	208 %
20 kPa	1.91mm	<u>2.37mm</u>	6.56mm	7.34mm	210 %
25 kPa	1.42mm	<u>2.08mm</u>	5.16mm	6.06mm	191%
30 kPa	1.14mm	<u>1.70mm</u>	4.11mm	5.17mm	204%

Table 27: Comparison Based on Different Imposed Loadings

Grouting Depth	Compaction Grouting (with cap)	Compensation Grouting (with cap)	Difference
5m	2.77mm	8.52mm	208 %
6m	1.63mm	7.32mm	349 %
7m	2.08mm	6.36mm	206 %
8m	3.60mm	8.56mm	138%

Table 28: Comparison Based on Different Grouting Depth with 15 kPa Loading

From the above data, when compared with the compaction grouting technique, the compensation grouting technique is far more superior in dealing with settlement control.

In addition to the above, there are other reasons as well: -

- a. Compaction grouting is a single-point and single-phase injection. The grout hole/pipe can only be used once. Thus it is required to inject all the predetermined grout quantity in one go whereas compensation grouting is a multi-points system and allows re-grouting according to the actual requirement. Economic consideration is only a minor issue. The ability to fine-tune the uplift of structures is the most concerned subject.
- b. Compaction grouting is used for treatment of granular soils. For treatment of cohesive soils, more research has to be done to acquire the technique. However, compensation grouting can be applied to both granular and cohesive soils.
- c. Contrary to the compensation grouting technique, it is more difficult to predict accurately the stress strain response of soil for compaction grouting treatment. The sudden increase (undrained condition) in volume strain by the grout bulb can lead to unpredictable response from the surrounding soil. The reason is that the soils are heterogeneous materials even though for the same type of soil strata.

- d. When the undrained condition changes to the drained condition, the soil volume decrease due to the dissipation of the excess pore water pressure. It is more in magnitude for treatment by the compaction grouting technique than the compensation grouting technique and is not desirable.
- e. For settlement compensation, the compensation grouting technique is more efficient. Not only it can induce more settlement compensation, but also can do it in a more controllable manner.

Nowadays, more extensive developments and multi-disciplinary research is in progress to improve the accuracy and research to improve the accuracy and reliability of the tools for compensation grouting.

According to Gilles Bucket et al (1999), there are three main themes of research: -

- 3D soil modeling tools of structural movements and grouting works for use on daily basis to monitor the compensation process.
- A new series of software for the direct control of grouting and of structure movements, and organizing the feedback with the 3D model.
- A new system of fibre optics sensors e.g. strain sensor and inclinometer using the fibre Bragg gratings with rugged logging units.

Amongst the other ground treatment techniques, compensation grouting is unique in settlement compensation. Its development, as seen from the above, involves quite a substantial utilization of the cutting edge IT expertise and software engineering.

Chapter 7. Conclusions

- i. It is possible to design a grouting scheme to change a groutable soil to possess the desired ground properties.
- ii. Different grouting techniques have different grouting mechanisms, which will produce different ground treatment result. Proper choice of grouting technique is important to the application of grouting in solving geotechnical problem.
- iii. There may be more than one grouting technique that can solve one particular geotechnical problem, but precautions to take during the construction work, progress and cost level maybe quite different.
- iv. Finite Element Method can be used to model and analyze grouting to define the extent of grouting required i.e. treatment zone dimensions and degree of ground properties improvement.
- v. Grout curtain with permeability equals to 1×10^{-6} m/s is found to be adequate for most water stopping usages.
- vi. It is important to extend grout curtain to top of less permeable soil strata in order to get a better sealing effect if this layer of soil is not too deep.
- vii. The jet grout plug should be located as near as possible to the final formation level in order to have the minimum cofferdam deflection due to excavation.
- viii. There exists always an optimal thickness of a jet grout plug to reduce cofferdam deflection.
- ix. Compensation Grouting is much more efficient than Compaction Grouting technique in dealing with ground settlement control.
- x. For better settlement alleviation or structure uplifting, it is important to inject grout just above a firm layer of soil for both the Compaction and Compensation Grouting techniques..
- xi. Cap enhancement is more obvious for Compaction Grouting technique than the Compensation Grouting technique.
- xii. Higher “cap” strength brings no better benefit to settlement improvement than cap strength 25% higher than the surrounding soil.
- xiii. Soil permeability has no effect on settlement improvement.
- xiv. Settlement improvement by both Compaction and Compensation grouting techniques are inversely proportional to the imposed loadings.

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Appendix A: Different Types of Grouting

By Grouting Materials

- Cement Grouting
- Bentonite Grouting
- Cement Bentonite Grouting (also known as Bentonite Cement Grouting)
- Chemical Grouting (or called Silicate Grouting)
- Resin Grouting

By Grouting Methods

- Permeation Grouting
- Jet Grouting
- Tube-à-Manchettes Grouting
- Pressure Grouting
- Prepack Grouting
- Hydro-Fracture Grouting

By Grouting Purposes

- Consolidation Grouting
- Compaction Grouting
- Compensation Grouting
- Curtain Grouting
- Plug Grouting
- Contact Grouting
- Impermeability Grouting

By Ground / Features to be Grouted

- Rock Grouting
- Soil Grouting
- Fissure Grouting
- Cavity Grouting
- Toe Grouting
- Alluvial Grouting

By Sequence of Work

- Pre-grouting
- Post-grouting

University of Southern Queensland
FACULTY OF ENGINEERING AND SURVEYING
ENG4111/2 Research Project
PROJECT SPECIFICATION

FOR: **CHAN Man Piu**

TOPIC: Analysis and Modeling of Grouting and its Application in Civil Engineering

SUPERVISORS: Dr. R. Merifield

ENROLMENT: ENG 4111 – S1, X, 2005
ENG 4112 – S2, X, 2005

PROJECT AIM: The project is to identify different types of grouting techniques, analysis methods, working models and its application in civil engineering.

PROGRAMME: **Issue A, 21st March 2005**

1. Research the background information of different types of grouting techniques.
2. Design working models for different types of grouting techniques and link the models to practical applications in civil engineering.
3. Research different analytical methods for selected grouting techniques.
4. Evaluate the different geotechnical considerations of selected grouting techniques.
5. Research information about the grout materials, plant and equipments as well as construction methods of selected grouting techniques.
6. Compare the advantages and limitations of the selected grouting techniques.

7. Research the advance of grouting techniques, grout materials and equipments.

As time permits:

8. Compare grouting technique with other ground treatment techniques.

AGREED:

Chan (Student) B. M. L. (Supervisors)

21/3/2005 7/4/05 / /